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PROPULSION ENGINEERING RESEARCH CENTER

1994 ANNUAL REPORT

VOLUME I

NOVEMBER, 1994

A UNIVERSITY SPACE ENGINEERING RESEARCH CENTER

106 RESEARCH BUILDING EAST
UNIVERSITY PARK, PENNSYLVANIA 16801

PROPULSION ENGINEERING RESEARCH CENTER

NASA UNIVERSITY SPACE ENGINEERING RESEARCH PROGRAM

ANNUAL REPORT 1994

VOLUME I

THE PENNSYLVANIA STATE UNIVERSITY
UNIVERSITY PARK, PA

Contents

EXECUTIVE SUMMARY

The Propulsion Engineering Research Center had another very successful year in 1994, and stands as a mature and potent contributor to our country's efforts in propulsion. Overall, the Center continued to make all its marks toward meeting its original mission as one of the University Space Engineering Research Centers. We have an integrated program that combines four basic elements: student education; a propulsion-focused research program; minority recruitment; and service to the propulsion community. The Center is a key and productive member of the propulsion community, and is well-positioned to make an evolutionary move to a self-supporting research center.

The Center is comprised of faculty, professional staff, and graduate and undergraduate students, as well as computational and experimental laboratories. The research program encompasses research issues related to liquid, solid, and hybrid chemical propulsion, and anti-matter and electric propulsion. Significant research efforts in propulsion for air and land transportation augment the space propulsion focus. Government propulsion laboratories and the U.S. propulsion industry are involved extensively in the program, and now support about 70% of the Center's research, with most of the remainder coming from the base USERC grant. Most of the base grant is used to support graduate students, and starting in 1995, the base grant will be used exclusively to support students.

Our primary mission is student education in classical engineering and science disciplines upon which propulsion applications are built. Students receive formal training in a traditional academic program and receive research training under the direction of their advisors and senior research staff. The number of well-qualified U.S. students who wish to pursue graduate research at the Center remains high. Over this reporting period, 96 graduate students and 22 undergraduate students were involved in research at the Center. To date, 78 students from the Center have graduated from Penn State with advanced degrees in engineering and science. Twenty-eight of the 78 have gone on to careers in U.S. propulsion-related industries, while ten graduates are now located at government labs, and ten graduates have begun their own research programs at academic research institutions. In the last reporting period, 21 students graduated with advanced degrees. At our current size, about 20 students from the Center graduate each year with advanced degrees.

The past year was marked mostly by consistent achievement. Not all the news was positive, however, and significant challenges were faced on several fronts. A general lull in the space program jeopardized our on-going research programs, and the softness of the employment market made student placement quite difficult in the space arena. Finally, NASA announced that in 1995 it will initiate a multi-year process to shift its support for university research away from the USERC program and into other avenues. In light of this redirection, we will be challenged to maintain all the beneficial aspects of the current program, especially in the areas of minority recruitment, community service, and discretionary research in new topical areas. Of course, activities in the educational and research areas will continue with the high standards that have been established in these areas.

The adversity we faced last year was offset by a number of positive factors that arose from the Center's strengths and capabilities that were developed with the support of the USERC grant. First, several major new research initiatives were awarded to Center researchers that will provide a stable basis for future research endeavors. Second, Center students have been quite successful in obtaining employment in areas other than space propulsion, and increased funding for research obtained from external sources has allowed us to retain some graduates in the Center as research staff. Third, NASA has committed support for existing Center students through their graduation; this has a particularly large impact at Penn State, since we have consistently placed a high percentage of the base grant funds into student support. Fourth, the College of Engineering at Penn State has made a long-term commitment to continue its significant support of the Center. Finally, the President's new space launch policy offers promise of a recovery in the space transportation field which will bode well for our Center in the future.

We have shown that we are able to respond to the needs of our country's space program in a timely and efficient manner. This ability arose from the support from the USERC program and our commitment to the ideals of the USERC program. As our research program continues to gain momentum, we expect that the Center will play a larger role in the future of our country's space program.

EXECUTIVE SUMMARY

Significant Events and Achievements of the Past Year

Externally-funded research support from industry and government labs increased to more than $3M in the past year. The number of funded research projects increased to 43, up from 36 a year ago. Research is sponsored by the NASA field centers, DOD laboratories, and the industrial community. The Center's success in attracting outside funding is a major indicator of its position in the propulsion community, and the high regards the community has for research perfomed by faculty, staff, and students of the Center. Significant new starts include studies on hybrid propulsion, tri-propellant combustion, and oxidizer-rich processes.

In our Minority Program, we initiated a new emphasis on collaborative efforts in research and education with selected Historically Black Colleges and Universities. Initial contacts were made with the Aerospace Engineering Department at Tuskegee University and with the Mechanical Engineering Department at Howard University, and visits to each campus were made by the Director and Assistant Director. Following a reciprocal visit by two professors from the Aerospace Engineering Department at Tuskegee, an Assistant Professor of Aerospace Engineering and two undergraduate students from Tuskegee University spent the summer of 1994 at Penn State. Collaborative research projects are currently being discussed between several research groups, and faculty from the Penn State Aerospace Engineering Department are consulting with their Tuskegee counterparts on plans to begin a graduate program in Aerospace Engineering at Tuskegee.

The Cryogenic Combustion Laboratory, the cornerstone of the Center's experimental program, is efficiently providing data for a number of combustion studies at high pressure conditions. New measurement techniques have been developed for application in these studies. Quantitative measurements of stable and transient species concentrations, heat flux measurements, propellant drop size distribution, and drop and gas velocity measurements have been made. The capabilities of the Cryogenic Combustion Laboratory have been upgraded considerably to support NASA's initiative to develop a new reusable vehicle. A liquid hydrocarbon flow capability has been added, giving the Laboratory full operability with liquid and gaseous oxygen, gaseous hydrogen, and liquid and gaseous hydrocarbons. In support of NASA's interest in a new reusable launch vehicle, combustors have been tested with oxygen-hydrogen-hydrocarbon tripropellant combinations, and oxygen-rich combustion has been demonstrated at oxygen/hydrogen mass ratios over 175. A comprehensive research program on injectors has been extended to include gas/gas injectors.

Our interactions with the propulsion community are numerous and substantive, as clearly evidenced by the broad research support noted above, and the Center has an international reputation for research excellence in propulsion. Interactions include numerous technical presentations at national and international conferences; publications in refereed technical volumes; public service through active participation on national technical committees, panels, and consortia; and most importantly, career placement of Center students throughout the propulsion community. Of the 21 Center students who graduated with advanced degrees this past year, five started working in a propulsion-related industry in the U.S. and five are working at academic research institutions in the U.S. A number of individuals visited the Center to review our program, representing various NASA centers, the Air Force, all major U.S. engine contractors, and several international corporations and laboratories. Two NASA employees participated in our NASA Seminar Series.

Two Ph.D. students from the Center, Michael Foust and Joseph Oefelein, were awarded the AIAA Liquid Propulsion Technical Committee Graduate Scholarship Award, presented annually at the Joint Propulsion Conference. These awards mark the fourth time over the past six years that students from the Center have been recognized in this way.

The Sixth Annual Symposium was held at the Lewis Research Center in September. The Center's Symposium has developed into one of the premier technical meetings on space propulsion in the world, with over 100 registered participants at this year's meeting representing government laboratories, NASA headquarters, small business contractors, and all the major rocket engine contractors. Forty-seven papers were presented. Eighteen of the 47 presentations were made by Center students. The Seventh Annual Symposium will be held at the Marshall Space Flight Center in September, 1995.

INTRODUCTION

The U.S. has an urgent need for improved propulsion technologies for launch and upper stage vehicles. Increased space activity globally, entries into the commercial market by Russia and China, and a growing awareness that old fleets of launch and trans-orbital vehicles cannot compete with newer vehicles has led to increased development activity in countries with major space programs. There are a growing number of countries in Europe and Asia with viable space programs. The present National Space Transportation Policy as put forth by the Office of Science and Technology restates the criticality of the U.S. space program in terms of achieving national goals, and recognizes that reliable and affordable access to space is a fundamental goal of the space program.

The Propulsion Engineering Research Center at The Pennsylvania State University plays an important role in our country's strategy to gain routine access to space through improved propulsion technology. The Center's objectives remain unchanged from those espoused at the time the Center was established in 1988. Specifically they are: (1) to provide a continuing supply of graduates at all degree levels for the propulsion community; (2) to conduct focused research that leads to improved technologies in propulsion; (3) to enhance participation in engineering by under-represented minorities; and (4) to interact with and aid industry by disseminating research results and performing various community services.

Our general approach toward achieving these objectives has been to develop a broadly-based research program that will attract U.S. students to study at the Center and U.S. government laboratories and propulsion contractors to fund Center research. There are four basic elements of our program:

- A diverse and fundamental research program oriented toward space propulsion applications with its roots in the classical engineering and physical sciences;
- State of the art laboratories for experimental and computational studies;
- A well-integrated selection of propulsion-based and propulsion-related courses at both the undergraduate and graduate levels; and
- Long-term support for an integrated core of students and research staff to study a wide scope of propulsion-related problems.

The Center's success in meeting its objectives is clearly indicated. An excellent group of students have undertaken graduate study at the Center to continue their graduate studies in propulsion-related sciences. The benefit to our country's propulsion industry is most clearly evidenced by thirty-eight students with advanced degrees from the Center who have gone into the U.S. propulsion community as permanent employees. Currently there are 96 graduate students and 22 undergraduate students participating in propulsion research at the Center, three-quarters of whom are U.S. citizens. The enrollment of minority

graduate students in the Departments of Mechanical and Aerospace Engineering has been impacted in a definite and positive way by our program to recruit minority students, and innovations to increase the efficacy of this program are being implemented. Research support from industry and government laboratories has grown substantially each year, and now exceeds the support from the USERC grant by a factor of three. These research efforts are directed by a total of eighteen faculty from four different University departments, and are disseminated to the community through a number of ways including our own Annual Symposium on Space Propulsion.

The Center has become an important part of the propulsion industry in the U.S. We have been partners in cooperative research efforts with all the major U.S. government rocket propulsion agencies and all the major U.S. liquid propulsion contractors. The Center is a major resource for the propulsion community and provides both a basis for technology advancements and graduates in science and engineering with a sound technical background to work on the challenges of space, air, and land transportation.

The research program encompasses three broad propulsion areas: space propulsion, air-breathing propulsion and internal combustion engines. The primary emphasis in the space propulsion work is on chemical rockets, including solids, liquids and hybrids, with a secondary emphasis on advanced propulsion concepts. The focus is on liquid rockets, most specifically combustion devices, along with some turbomachinery efforts. The work in advanced propulsion concepts includes several different topical areas that provide breadth to the Center's space propulsion efforts. The air-breathing work is focused on combustion-related issues in gas turbine engines, while the internal combustion work addresses similar combustion-related topics in both spark ignition and Diesel engines. These complementary topics are well integrated into the Center and provide important synergism by ensuring that our students acquire a broad overview of propulsion and that technology transfer is stimulated.

The present document has been prepared to describe the status of the Propulsion Engineering Research Center and its progress over the period from November 1993 through October 1994. In Volume I, an overview of the Center's organization is presented along with information on the Center's current status and accomplishments in three areas tied to our primary objectives - Education, Propulsion Community Interactions, and Research. Appendices in Volume I include information on past and present faculty and student involvement along with a listing of publications and presentations. Volume II of this report contains the Proceedings of the Propulsion Engineering Research Center's Sixth Annual Symposium, where more detailed information on current research at the Center can be found.

ORGANIZATION

The Center is comprised of an integrated group of students, faculty, and staff looking to provide fundamental solutions to a diverse set of problems related to propulsion. The key individuals involved in the management of the Center are identified in Table 1. The USERC program is managed through NASA Headquarters. The Center Director acts as Principal Investigator, and is generally responsible for the Center. The Director, along with the Associate Director and the Assistant Director develop and implement policies and strategies for research and education relevant to the propulsion needs of our country.

The Center's Policy Advisory Board is made up of propulsion experts from NASA, industry and academia. This group is charged with helping to guide long range development to ensure that the Center can capably respond to the nation's space propulsion technology needs. The Policy Advisory Board met twice during the present reporting period to evaluate the overall progress of the Center from an objective, external viewpoint, and to advise in matters of policy and research emphasis. This year Professor Warren Strahle passed away. Professor Strahle was an original member of the Board who made a number of valuable contributions to the Center; he will be greatly missed. The Technical Review Committee is composed solely of NASA personnel, and represents NASA Headquarters and the Lewis, Marshall, and Jet Propulsion Laboratory field centers. The Technical Review Committee is charged to evaluate the Center's progress and to make recommendations regarding the Center to the Director and to the USERC Program Manager.

A primary responsibility of the Center Director is to allocate USERC funds according to Center objectives. A breakdown of the actual distribution for 1994 is shown in Figure 1. As has been the case in previous years, funding for students was the dominant portion of the USERC funds expended. This distribution of USERC funds reflects the primary USERC objective - student education. Funds allocated to students include direct student support in the form of NASA traineeships and research assistantships, as well as the payment of tuition and fees. While approximately half of the Center funds go directly to student support, most of the remainder indirectly supports the student program via administration, equipment purchases for student research, and salaries for experienced staff to help faculty direct student research.

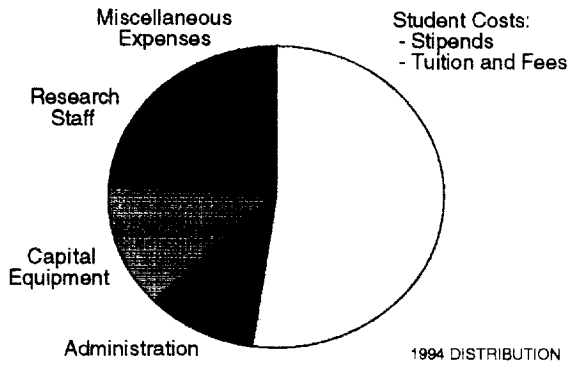


Figure 1. USERC funds are distributed according to Center goals.

Table 1. Organization and Management Structure

USERC PROGRAM MANAGEMENT

Mr. Gordon Johnston, USERC Program Manager,
Office of Advanced Concepts and Technology, NASA Headquarters

CENTER ADMINISTRATION

Dr. Charles Merkle, Director and Professor of Mechanical Engineering
Dr. Robert Santoro, Associate Director and Professor of Mechanical Engineering
Mr. William Anderson, Assistant Director
Mr. John Raiser, Administrative Coordinator

POLICY ADVISORY BOARD

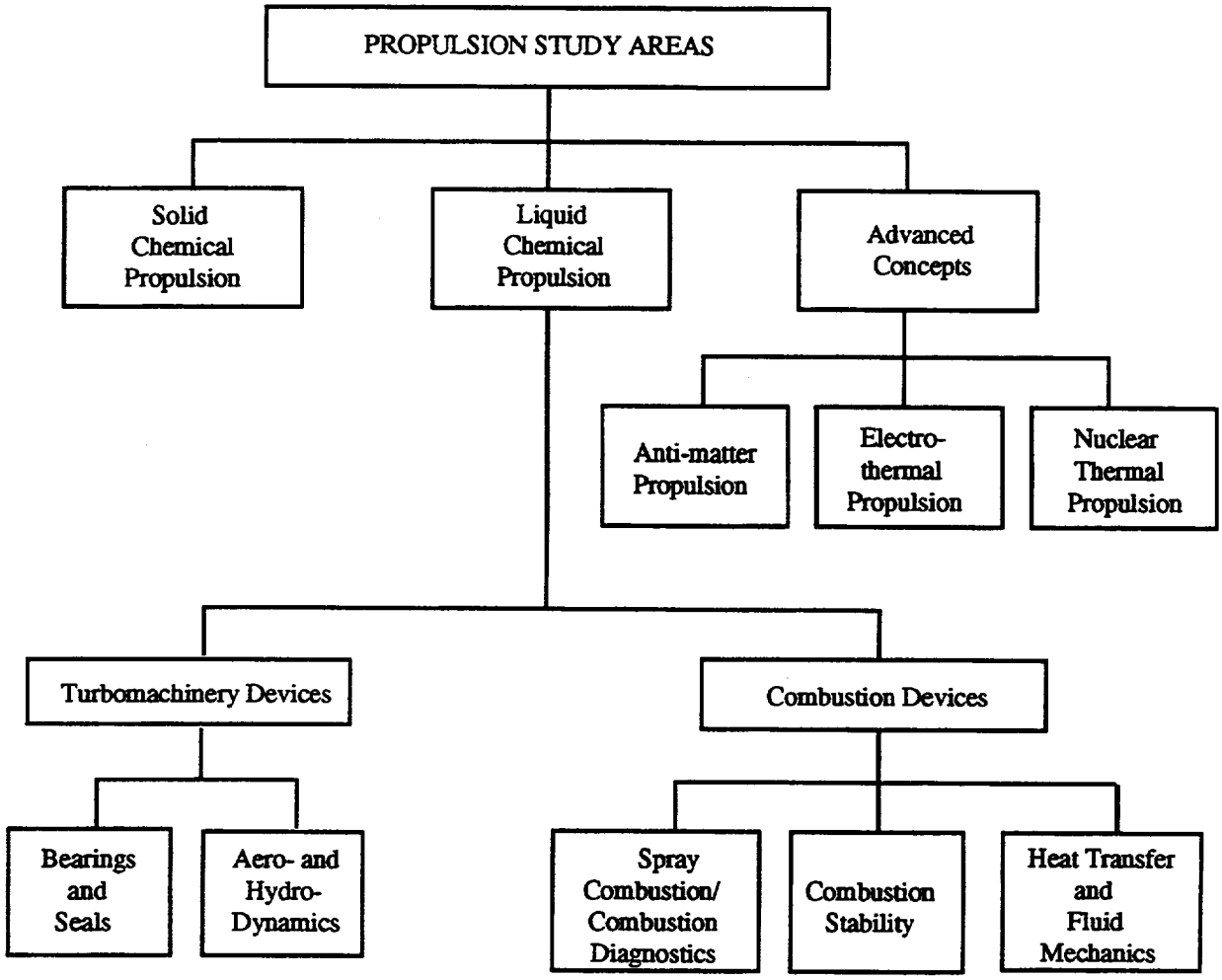
Dr. Robert Corley, Chief Scientist, Propulsion Directorate, Air Force Phillips Laboratory
Mr. George Cox, Group Leader, Combustor and Augmentor Design, Pratt & Whitney
Dr. Larry Diehl, Chief, Space Propulsion Technology Division,
NASA Lewis Research Center
Mr. Stephen Evans, Director of Advanced Technology Programs,
Rocketdyne Division, Rockwell Corporation
Mr. Robert Sackheim, Deputy Director of Propulsion and Fluid Mechanics Center, TRW
Dr. Adam Siebenhaar, Manager, Space Propulsion Programs,
Aerojet Propulsion Division, GENCORP
Mr. George Young, Deputy Chief, Component Development Division,
NASA Marshall Space Flight Center

TECHNICAL REVIEW COMMITTEE

Mr. William Escher, Technical Review Committee Chair, Earth to Orbit Program Manager,
Office of Advanced Concepts and Technology, NASA Headquarters
Dr. Larry Diehl, Chief, Space Propulsion Technology Division,
NASA Lewis Research Center
Dr. Philip Garrison, Manager, Propulsion and Chemical Systems Section,
NASA Jet Propulsion Laboratory
Mr. John McCarty, Chief, Propulsion Laboratory, NASA Marshall Space Flight Center

The USERC grant was a major factor in recruiting well-qualified students to the Center, and there has been a steady increase in both the number and quality of the applicants. Students were attracted by the availability of direct student support, the reputation for research excellence in propulsion, and the visibility of being associated with the Center. Throughout the first five years of the Center, USERC funding enabled us to commit support to outstanding students early in the recruiting year, while providing the student a broad selection of project and technical areas in which to work. Another factor in student recruitment was the acquisition of major research equipment that enhances the quality and relevance of our research efforts. Finally, the USERC grant has impacted both student recruitment and student education through enabling the assembly of a core of experienced research staff to help guide students in their research, and to provide support to maintain a small but effective administrative infrastructure.

FIGURE 2. PROGRAM STUDY AREAS IN PROPULSION



USERC funds were also used to establish the direction and focus of the Center's research program at its outset, and to ensure that the Center's research efforts are integrated and mutually synergistic. The structure shown in Figure 2 was planned and was determined largely in the early phase of the Center when specific research areas were nurtured with funding from the USERC grant. The space propulsion arm of the Center's research program consists of three main areas that cover most space transportation applications: liquid chemical propulsion, advanced propulsion concepts, and solid chemical propulsion. The breadth across propulsion areas shown in Fig. 2 exposes our students to a variety of significant propulsion technologies including those representing long-term applications. The research emphasis in space propulsion is on liquid chemical propulsion, which is the dominant area of interest to the U.S. space program today and in the foreseeable future.

The liquid chemical propulsion emphasis is segmented into two focal areas that contain the bulk of the research being performed at the Center: combustion devices and turbo-machinery. Depth in the liquid

rocket area promotes synergy between individual research projects and stimulates research excellence. Strong combustion research programs in gas turbine, diesel, and spark ignition engines also exists within the Center that complement the combustion and turbomachinery liquid rocket research. Additional turbomachinery and materials research programs at the University also provide a major resource to Center personnel through course work and formal and informal interactions.

Since an end goal of the USERC program was that the Center become self-sufficient, two recent strategies have been to re-program funds to enable new research initiatives in discretionary areas, and to continue to build our experimental and computational capabilities. Wise investments in discretionary research funding and capability resulted in major new awards this past period in hybrid propulsion, tri-propellant combustion, and oxidizer-rich flows. These major awards resulted in another large increase in the amount of support obtained from outside sources in 1993. An illustratration of the history of the relative distribution between USERC funding and outside funding is shown in Figure 3.

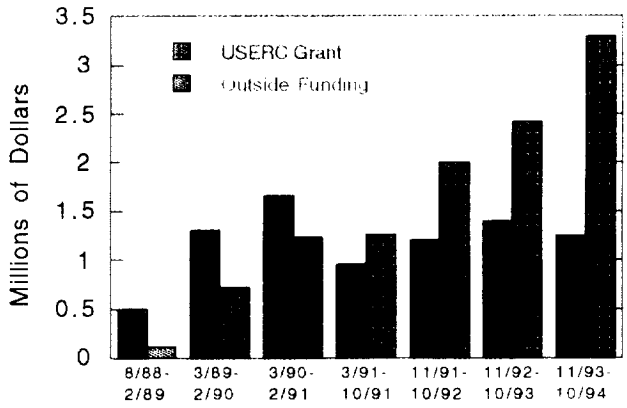


Figure 3. The USERC grant provided the basis for the development of a research program now funded predominantly by external funds.

The recognition that the students, faculty, and staff of the Propulsion Engineering Research Center represent a significant resource is indicated in Figure 4, which shows the present relative research support between industry, government laboratories, and the USERC grant, as well as support received from the university and through fellowships and scholarships. It is important to note that the Center became a resource for the U.S. propulsion community on the foundation provided by the USERC grant. A mechanism to replace this key ingredient is needed to ensure continued success of the Center.

Recruitment of minority students and interactions with the propulsion community are other Center efforts enabled by the USERC grant. Interactions with others in the field have naturally become more extensive as the amount of externally-funded research increased. A number of faculty, staff, and students have contributed to the success of the minority program, which required a concerted effort and funding from the base grant. The minority program was oriented toward undergraduate students over its first four years, and has positively impacted the diversity of our student population. Twenty-two students have participated in our minority program, of whom many have gone on to graduate school.

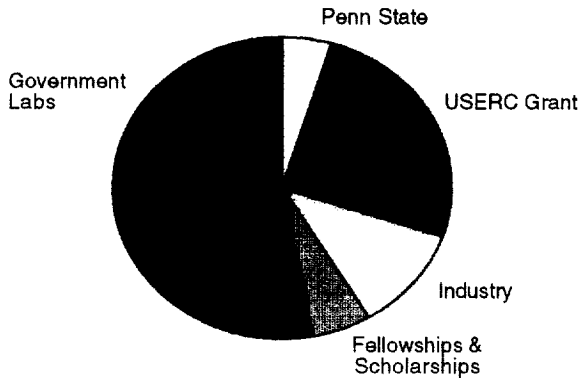


Figure 4. Center research program is widely supported.

A final aspect of the Center's structure is the continuing support from the University. The University recently made a long-term commitment to pay half the administrative costs of the Center and to provide matching money on major equipment purchases. The University has also been generous in providing research space. We presently occupy three-quarters of a modern, three-story research building. These co-located offices and laboratories have been an essential ingredient in the Center's progress by enhancing interactions between students and faculty. A remote test site was also allocated and refurbished by the University to allow the development of the Cryogenic Combustion Laboratory, which is a key component of the Center's research program. Lab and office space allocated to the Center presently stands at about 18,000 square feet. Additional University support includes fellowship awards to several Center students and overhead sharing.

In the last period, NASA announced its plans for an orderly transition of all the USERC's to a self-sufficient status. Starting in 1995, all USERC funds will go directly to supporting students who were resident in the program in 1994. NASA has committed to continue this support through the students' graduate careers. The immediate effects of the decision to transition to self-sufficient operation probably impacted us less than any other USERC, since we have historically placed most of the USERC grant into student support, and thus there was a large number of students eligible for continued NASA support. However, the long term impact will be serious and the Center administration and the Policy Advisory Board will focus on this key issue this year.

We have shown that we are able to respond to the needs of our country's space program in a timely and efficient manner. We purposefully developed this ability, which arose from our commitment and NASA's support through the USERC program. We are challenged now to maintain our capabilities and research focus, and to keep our productivity at current levels without the basis of support the USERC program has provided.

Our plan is to continue the Center with as little interuption as possible. Although USERC funding levels will be gradually reduced, we have worked to place ourselves in a competitive position to obtain funding for research through initiatives from government labs, and we expect that an increase in externally-funded research programs will help to maintain the current research activity. The Center's role in

the propulsion community will become more important in the future as our research program continues to gain momentum and as corporate labs shift their attention toward more applied research.

Without a major new development effort in space transportation, we expect most of our graduates will be hired by small firms working in space propulsion or by companies outside the propulsion field. We also anticipate being able to continue to hire some Center graduates as post-doctoral research staff. We have already shifted the empasis in the minority program toward research collaborations with HBCU's; without the USERC grant, the support to enable these efforts must now come directly from a specific funding agency. Without a centralized thrust, these interactions must be initiated and followed through by individual faculty members. Since the Center is an established research institution with an international reputation for research excellence, most of the important community interactions will still come about through individual faculty and staff. However, some of the community services that the Center has provided in the past, for example, hosting the First International Symposium on Liquid Rocket Combustion Stability, will be difficult to continue.

EDUCATION

Education is the Center's foremost role. We have made major efforts to attract students whom are motivated and highly-qualified, and to better the diversity of the student population. The students in the program have been outstanding and are a convincing and visible demonstration of the Center's effectiveness. A number of features are incorporated into the Center to attract these quality students. Primary among them are an active and visible research program in an exciting technical area; a highly respected faculty; modern and well-equipped experimental and computational laboratories; a good selection of courses related to propulsion; and an attractive physical plant.

The number of well-qualified U.S. students who chose to focus their graduate studies on propulsion grew again in 1994. Figure 5 gives a historical perspective of student participation at the Center since its inception. As seen from Figure 5, the primary focus of the Center's educational program is at the graduate level, and is augmented by significant undergraduate involvement. Ninety-six graduate students worked on research projects in air, land, and space propulsion applications in the present reporting period. Our graduate students come from undergraduate programs widely dispersed across the United States, as well as from countries from around the world. Over 70% of the graduate students are U.S. citizens. During this reporting period, four NASA employees and three Air Force employees were students at the Center. Appendix A includes a list of Center students.

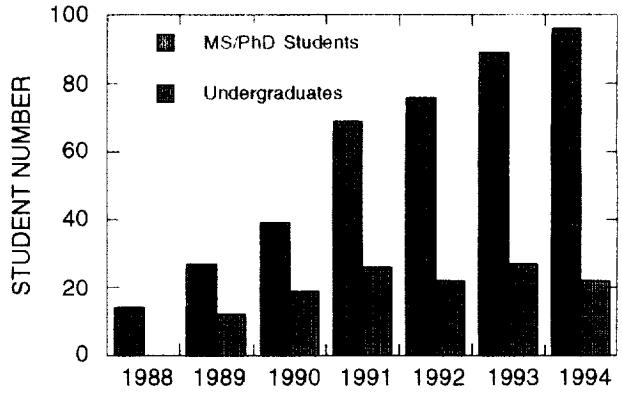


Figure 5. Student participation at the Center continues to grow.

Since its inception, the Center has also had a program to enhance minority participation in the space program. Our first efforts, which were channeled into the Summer Undergraduate Program, were oriented toward providing minority undergraduate students in science and engineering with a research experience in a propulsion-related area. The program was designed to provide the minority undergraduates with a first-hand experience of graduate school and to acquaint them with career opportunities in science and engineering. The number of minority students in our own graduate program was also impacted positively by the Summer Undergraduate Program.

A new minority emphasis was initiated during the past year that is designed to build substantive ties with individual faculty at minority academic institutions and to provide a more direct impact on our graduate program. The first steps were taken when members of the Center visited Tuskegee University and Howard University. Interactions with the Aerospace Engineering Department at Tuskegee have gone exceptionally well, and as a result, Dr. Eric Sheppard from Tuskegee spent the summer of 1994 at the Center working on computational studies of reacting shear layers. Two Tuskegee undergraduate students also spent the summer at Penn State as summer interns. The future of the Tuskegee - Penn State effort looks quite bright. Collaborative research efforts between the two schools are being pursued, and these will probably serve as a model for many of the Center's future efforts in this area. It is currently envisioned that students and faculty from the minority institution will have access to the Center's excellent experimental and computational facilities as part of these interactions.

Undergraduates are involved in the propulsion program through their participation in our research efforts and through classroom teaching by Center faculty. Undergraduate research involvement is fostered by summer programs that are open to undergraduates from across the U.S. Penn State undergraduates are involved at the Center throughout the school year. Bringing undergraduates into the Center to assist in research is an effective way of encouraging them to consider careers in propulsion as well as further studies in graduate school. Each undergraduate is assigned an individual faculty adviser and a graduate student mentor. Undergraduates work on a particular research project alongside graduate students to provide them with a first-hand glimpse of research and graduate school. In the present reporting period, a total of 22 undergraduates were involved in research at the Center.

Graduate students in the Center have been generally supported as a NASA Trainee, a Research Assistant, or a NASA Graduate Student Researcher (GSRP). NASA Traineeships have been funded out of the USERC grant and provide fellowship support for students having exceptional academic records. Research Assistantships are funded either by external grants or by the USERC grant. The GSRP award is funded on a competitive basis by the individual NASA centers. Center students who have been recipients of various scholarship awards are listed in Table 2.

The faculty and students that comprise the Center are drawn from the College of Engineering and the College of Science. In the College of Engineering, the Departments of Aerospace Engineering, Engineering Science and Mechanics, Mechanical Engineering and Nuclear Engineering are involved, while the Department of Physics represents the College of Science. The faculty in the Center work individually with the Center students as research advisors, providing specialized training in research for all students, and provide formal instruction in the classroom.

Table 2. 1994 Trainees and Fellows

NASA Trainees

Philip Buelow, Mechanical Engineering
John Cramer, Mechanical Engineering
James Dailey, Aerospace Engineering
Ken Phillapart, Aerospace Engineering
Tom Prevish, Mechanical Engineering
Douglas Schwer, Mechanical Engineering
Kevin Wert, Mechanical Engineering
Lance Werthman, Aerospace Engineering
Joseph Wicker, Aerospace Engineering

NASA Graduate Student Researchers

Russell Daines, Mechanical Engineering
Michael Foust, Mechanical Engineering
Joseph Oefelein, Mechanical Engineering
Michael Ondas, Mechanical Engineering
Mark Schmidt, Mechanical Engineering

National Institute of Standards and Technology

Aaron Johnson, Mechanical Engineering

Palace Knight (Air Force Phillips Lab)

George Harting, Mechanical Engineering

AASERT (Air Force Office of Scientific Research)

Eric Boyer, Mechanical Engineering
Julian Laxton, Mechanical Engineering
Bryan Quay, Mechanical Engineering
Shamim Rahman, Mechanical Engineering

Students also have abundant opportunity to attend seminars given by invited speakers who are recognized experts in the propulsion field. One aspect of our educational program is the NASA Seminar Series, which has enhanced the students' awareness of the practical technology aspects of their research and career opportunities in propulsion. As seminar speakers, representatives from various NASA and Air Force locations come to the Center and receive an overview of the Center's projects, status, and goals, and conduct informal discussions with faculty and student groups during laboratory tours and demonstrations. The presented seminar is intended to give students and faculty alike an exposure to "real-world" concerns ranging from social to programmatic to technical issues. The seminars also serve to familiarize students and faculty with NASA capabilities and potential career opportunities. Speakers in this series to date have represented Lewis, Marshall, Kennedy, Stennis, Johnson, Langley and Headquarters as well as the Air Force Phillips Laboratory and the U.S. Congress. A list of seminar speakers over the past two years is given in Table 3.

Table 3. 1993-94 NASA Seminar Series Speakers

• June 20, 1994	Dr. Isaiah Blankson, NASA Headquarters "Research Needs for Hypersonic Vehicles"
• March 15, 1994	Mr. John Facey, NASA Headquarters "Emerging Technologies"
• November 4, 1993	Mr. Mark Fisher, Marshall Space Flight Center "Saturn and Shuttle Boosters"
• September 10, 1993	Mr. William Knuth, The University of Tennessee "Full-Flow, Staged Combustion Rocket Engines"
• September 8, 1993	Mr. Richard Ryan, Marshall Space Flight Center "Results from NASA's Access to Space Study"
• April 28, 1993	Mr. Dennis Bushnell, NASA Langley Research Center "Hypersonic Airbreathing Propulsion - Research and Applications"
• March 31, 1993	Astronaut Guy Bluford, Johnson Space Center "Space Transportation - An Astronaut's Perspective"
• January 15, 1993	Mr. Gerald Pitalo, Stennis Space Center "Propulsion Activities at the Stennis Space Center"

Finally, the Center's education program extends to K-12 students. Last year two high school students worked at the Center for two weeks under the direction of a senior graduate student. The students came to Penn State under the auspices of the Space Grant College program and worked on characterizing the effect of high ambient pressure on spray formation processes. Other interactions are in the form of presentations to youth groups and grade school students, an annual Open House for high school students interested in engineering, participation in the annual High School Student Intern Program in Engineering and Technology, and laboratory tours for the State College High School Science Club.

RESEARCH

The Center's research program was filled with highlights over the past year. In addition to a number of notable research achievements, several major new research projects were started that are core to NASA's goals of reliable access to space. External funding for research increased again considerably, and now exceeds the base USERC grant by nearly a factor of three. The six previous years of hard work have clearly come to fruition, and the value of the products of the Center's research program is evident.

Our space policy calls for more reliable and affordable access to space. Because the cost of developing an advanced launch vehicle will consume a large portion of our country's available resources, and operating costs even more, an accurate prediction of the proposed system's operational and performance characteristics is the key to selecting the right vehicle concept for development. Two propulsion technology areas that are being investigated are hybrid motors and advanced reusable launch vehicles. Three projects that utilize the Center's capabilities to directly support these areas were initiated this past year.

Hybrid motors offer the potential for safe and reliable boost. The Center's new project in this area is a collaborative effort between two research groups that will provide an engineering technology base for development of large-scale hybrid rocket motors as well as a fundamental understanding of the complex processes involved in hybrid propulsion. A hybrid motor test cell has been installed in the High Pressure Combustion Laboratory, where it will be used to produce data on the fundamental processes involved in fuel decomposition and boundary layer combustion. A companion analytical study is being conducted at the Center in the Computational Propulsion Laboratory.

Present space policy further calls for the development of a new reusable launch vehicle and specifically for an investigation into the technologies required to develop a single-stage-to-orbit (SSTO) capable vehicle. Two research programs were initiated at the Center in the last reporting period that support the SSTO effort: tri-propellant combustion and oxygen-rich flow and combustion processes. Tri-propellant liquid rocket engines use the H_2/O_2/RP-1 propellant combination to help achieve the low vehicle weight that is required for an SSTO vehicle. The use of oxygen-rich preburners may enable more robust liquid rocket propulsion systems. Both of these projects are comprised of companion experimental - analytical tasks conducted by collaborating research groups at the Center.

Our strategy to become a world leader in propulsion research called for the development of an assembly of unique experimental and computational capabilities. Extensive computational facilities include on-site microcomputers, workstations and mini-supercomputer, the University mainframe computer, and ready access to supercomputers at a variety of locations across the country. The Computational Propulsion Laboratory at the Center has a local assembly of 20 RISC 6000 workstations and a CRAY J-916, all

connected through ETHERNET to the University fiber-optics network and national supercomputer centers. The CRAY was added in anticipation of new research starts and to ensure Center researchers have access to the latest technology.

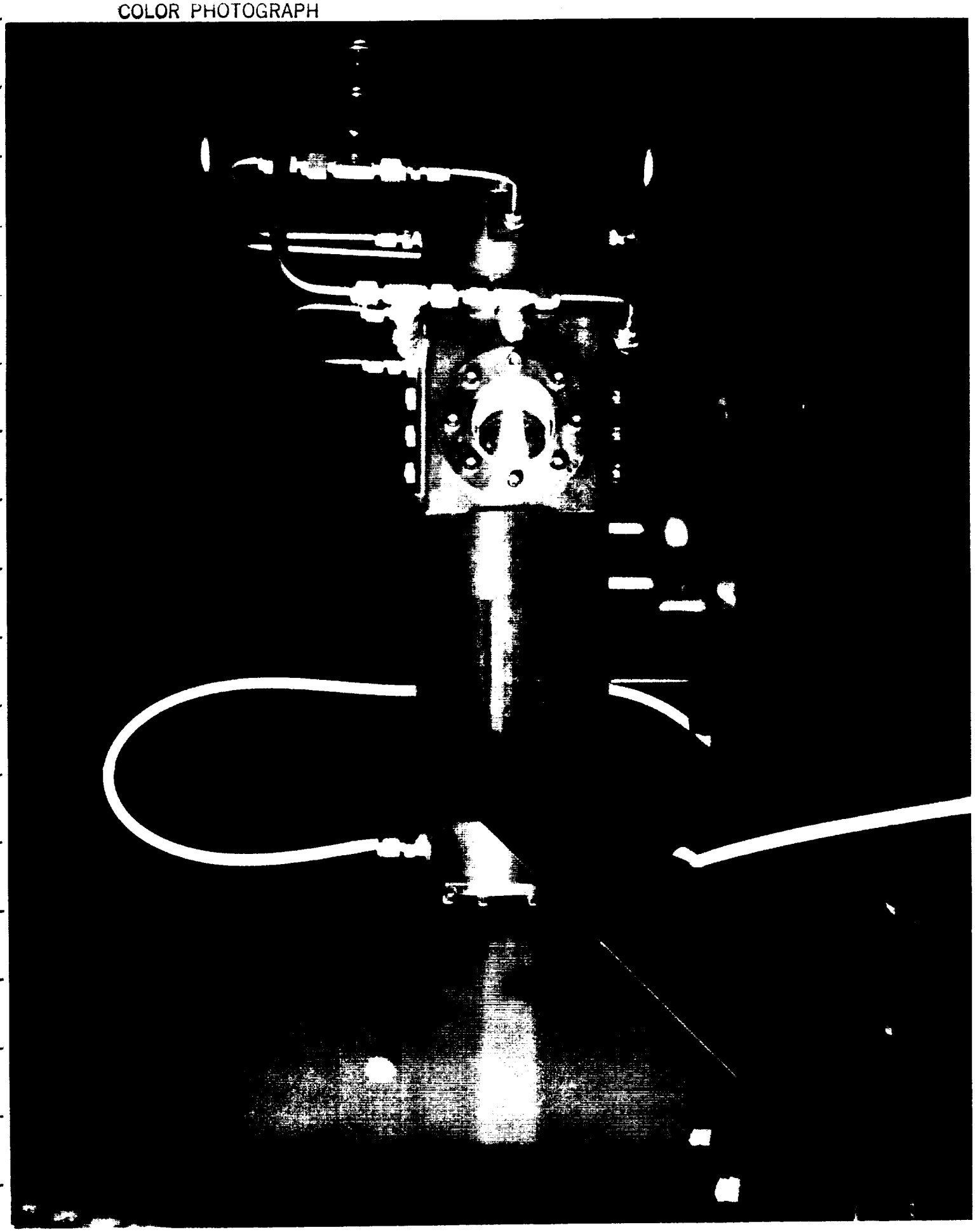
The Cryogenic Combustion Laboratory (CCL) is the cornerstone of our experimental program. This unique laboratory was developed to address a critical need of experimental facilities and research expertise necessary to study combustion, materials compatibility, and heat transfer under realistic conditions. On the following page, a photograph of Penn State's optically-accessible rocket at the CCL in operation with GH_2/GOX propellants and a shear coaxial injector is shown. Access for observation and measurement is allowed by a 2-inch diameter quartz window.

The two research emphasis areas at the Cryogenic Combustion Laboratory are the development and application of advanced diagnostic techniques for studying basic physical processes in rocket environments; and production of experimental data that are being used for a number of projects, including validation of reacting CFD codes, injector studies, tri-propellant combustion studies, oxidizer-rich process studies, and combustion instability mechanism studies. The laboratory consists of a test bay, a control room, an instrument room where most of the optical diagnostic equipment is located, and a gas storage area. The lab provides students with hands-on experience with rocket testing and with the safety and practical issues associated with handling cryogenic propellants. Its capabilities were recently upgraded to prepare for NASA's initiative for a reusable launch vehicle. Propellant flow capabilities include gaseous and liquid oxygen, hydrogen, and gaseous and liquid hydrocarbons with flowrates at the uni- and few-element scale (~ 1 lb/s) and test operating pressures to 1000 psia.

An overview of the space propulsion research underway at the Center in the areas of liquid propulsion and advanced propulsion concepts is given below. A few short descriptions of representative research results are provided for illustrative purposes. Extended abstracts of Center research projects in space propulsion are contained in Volume II of this report, the Proceedings of the Sixth Annual Symposium.

Liquid Chemical Propulsion

Our efforts in liquid chemical propulsion are designed to impact two practical areas: combustion devices and turbomachinery. In general the research efforts include a substantial experimental component with coordinated support in computational fluid dynamics (CFD) and/or other analytical areas. The work in combustion devices is comprehensive and encompasses spray combustion and spray diagnostics, combustion stability, and fluid mechanics and heat transfer. Extensive research activities in gas turbine and automotive engine combustion enhance the rocket work and provide cross-pollination of technology across the three



areas. The turbomachinery research focus area is comprised of research efforts on bearings and seals, and hydro- and aero-dynamics.

The main combustor of a liquid rocket engine is a critical component that largely determines the performance of the vehicle. The injector is a key combustor component because it controls the formation of propellant sprays and subsequent mixing and vaporization, and determines the conversion efficiency of chemical energy to thermal energy and the heating loads on the chamber walls. Increased understanding of the spray combustion process and its management will lead to more durable and more economical rocket engines. The Center has developed a comprehensive research program in spray combustion, focusing on the processes of primary and secondary atomization, droplet transport, and vaporization and reaction, with an emphasis on the development of new experimental techniques to study spray and combustion processes, application of these techniques to gain further understanding into the basic processes, and development of theoretical models for propellant atomization and vaporization.

Our experimental work in sprays includes complementary research on a broad subset of spray combustion issues that covers the important practical aspects. The common injector element types, impinging jet and shear and swirl coaxial jet injectors, are being studied to determine the incipient breakup mechanisms and to characterize the resultant spray field. These measurements are being compared to correlations currently in use by engine designers as well as providing validation data for mechanistic atomization models and input for CFD models. On the other side of the scale, individual droplets in isothermal, non-isothermal, and reacting conditions are also being studied to determine droplet drag, secondary atomization, ignition, and droplet heating characteristics. Experiments are also underway to provide data on evaporation and diffusion rates of LOX under a variety of conditions. Effects of sub- and super-critical thermodynamic operating conditions are being evaluated in the above experiments.

Analytical studies complement these experimental efforts. Development of mechanistic models of combustion processes is underway and model predictions are being compared to experimental data obtained at the Center and other research laboratories. Atomization models and models for two-phase non-isothermal phenomena in the near-critical and super-critical regimes are being developed. CFD models for reacting flows in combustor/nozzles are also being developed. An example of a cooperative research effort between an experimental group and a theoretical group at the Center is a project to obtain benchmark quality data to provide to the entire liquid rocket propulsion community for validation of CFD-based combustion codes. The optically-accessible rocket chamber shown earlier was designed jointly by the two research groups with the requirement that the experiment produce data appropriate for code validation. To date, measurements of OH radical concentrations, gas velocity, and the size and velocity of LOX droplets have been made. Results have been presented regularly at the CFD Consortium meetings held at NASA Marshall Space Flight Center, as well as at national meetings. Recent efforts have focused on the measurement of stable gas

species using Raman spectroscopy. Figure 6 shows concentration profiles of oxygen, hydrogen, and water measured in the optically-accessible combustor in a plane 1" downstream of the coaxial injector exit.

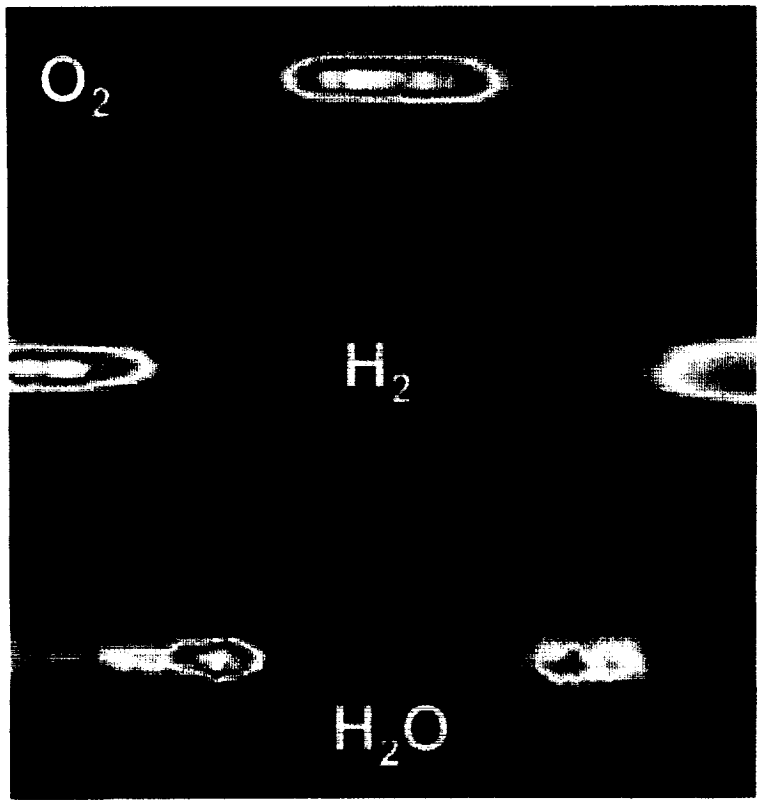


Figure 6. Concentration profiles of stable gas species in the optically-accessible rocket measured using Raman spectroscopy. This image shows concentration levels of oxygen, hydrogen, and water in a slice across the combustor centered 1" downstream of the coaxial injector exit. Oxygen is injected through a tube in the middle of the coaxial injector and hydrogen is injected through the annulus. Water is formed in the reaction zone. This data is useful to combustion modelers and injector designers.

The occurrence of high-frequency, high-pressure oscillations is a severe problem that has plagued rocket designers and one for which a mechanistic predictive design analysis capability is completely lacking. The Center has a comprehensive program in combustion instability that emphasizes the understanding of the underlying initiation and sustenance mechanisms and the development of mechanistic models that can accurately predict the instability phenomena. The two major injector types, coaxial jets (for LOX/H_2) and impinging jets (for LOX/HC and storable propellants) are being studied. The interactions between the unsteady flowfield and the primary combustion processes of atomization, spray formation, and droplet vaporization and burning are being studied both experimentally and theoretically. A CFD testbed is under development to evaluate combustion instability mechanisms numerically and for future use as a predictive design analysis tool.

One of the combustion instability projects underway is a study for the Air Force Office of Scientific Research (AFOSR) that seeks to identify combustion instability mechanisms in combustors using impinging jet injectors. Figure 7 shows the measured drop distribution of a water spray formed by impinging liquid jets for various values of an empirically-derived stability parameter (the ratio of the fuel's injector orifice diameter to its injection velocity) that describes the range of instability frequencies that the combustor can drive. The figure shows that, as the drop distribution produced by the impinging jet injector becomes narrower and the mean drop size becomes smaller, higher instability frequencies can be driven in the combustor. This result is used to help understand the root causes of combustion instability, and offers insight into appropriate strategies to deter initiation and growth of combustion instabilities.

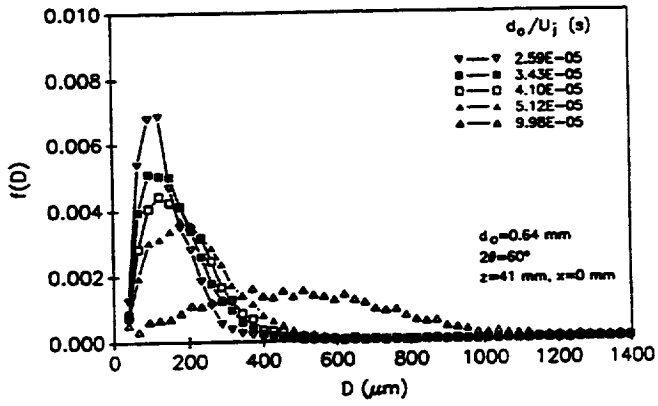


Figure 7. Distribution of drop size formed by impinging jets as the stability parameter, d_O/U_j, is changed. As the value of the stability parameter is reduced, the combustion process can couple with higher frequencies of instability.

The technology focus of present civil space transportation policy is on proving the concept of single-stage-to-orbit propulsion (SSTO), which potentially offers drastic improvements over current systems. Since development costs for an advanced space propulsion system will be enormous, the ability to accurately predict and evaluate the performance and operational behavior of potential propulsion systems is of paramount importance. The use of computationally-based models will play a key role in the design analysis process. Our research program in computational fluid dynamics emphasizes the development and validation of analytical tools for the study of combustor, nozzle, and cooling channel flowfields. In space based thrusters, for example, the majority of the fuel can be injected as wall coolant. The use of computational models to evaluate the effects of changes in injection design on near-wall mixing and combustion will lead to more optimal combustor design margins. Figure 8 shows three-dimensional contours of temperature and OH mass fraction in a small gaseous hydrogen/oxygen thruster being developed at the Lewis Research Center. The results show that vortical structures are formed that circulate oxidizer around the fuel jets toward the wall, causing high temperature regions downstream of the injection ports. Understanding these sorts of details will help designers obtain the results that are intended by their design. Results from these and other analyses are also being compared to experimental results underway at the Center and other laboratories.

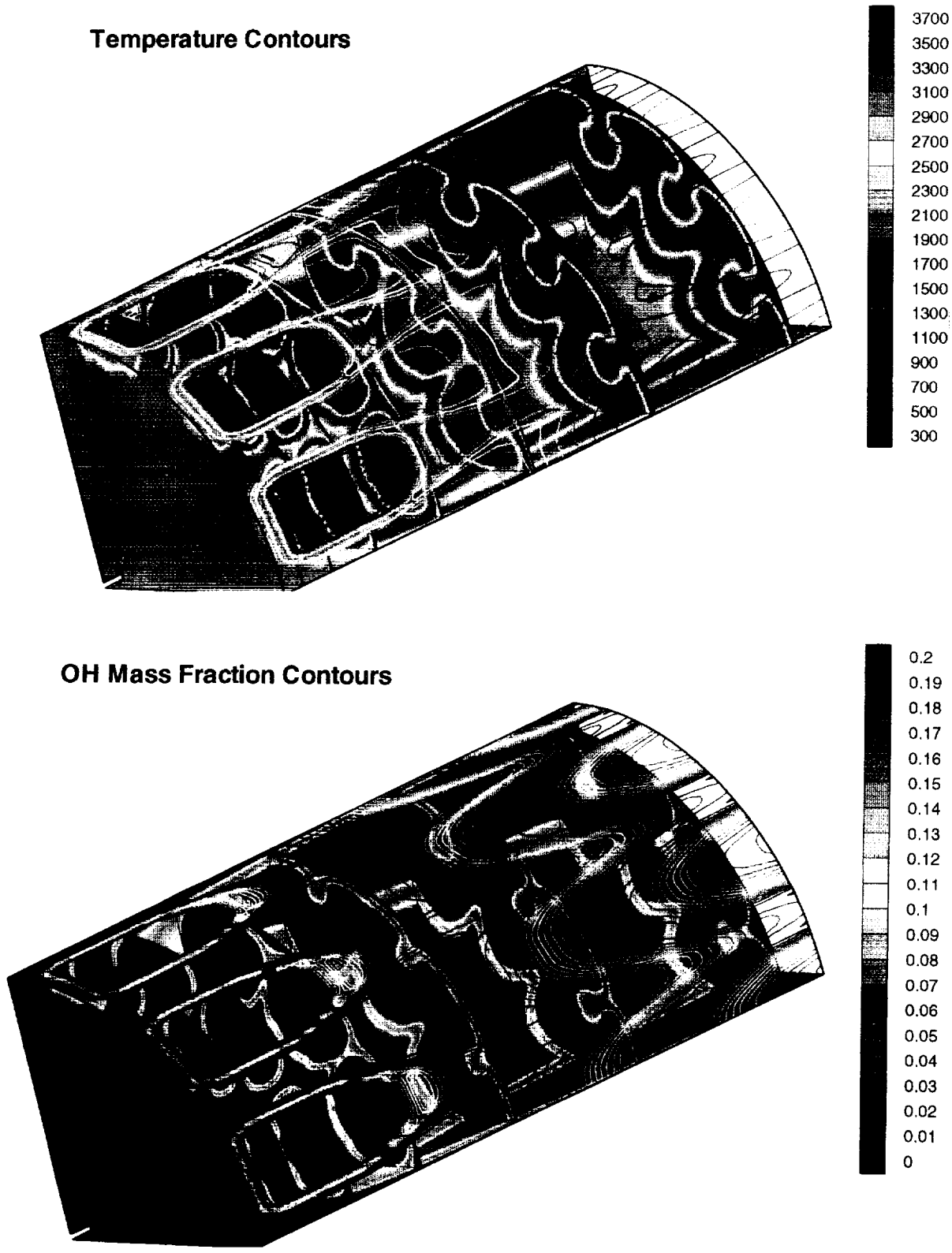


Figure 8. Three-dimensional contours of predicted temperature (K) and OH mass fraction in a small gaseous hydrogen/oxygen thruster. Mixing and combustion of the hydrogen fuel injected around the chamber periphery are being investigated. Contours for one quarter of the combustor are shown; three fuel injectors are modeled in this sector.

Advances in computational power are enabling simulations on a molecular level. A research program was initiated over the past period with AFOSR support to model the evaporation of droplets at supercritical conditions using molecular dynamics implemented on massively parallel processors. The forces between individual atoms or molecules are calculated from basic theoretical and empirical laws. Serial and parallel codes have been developed, and a data parallel code for implementation on CM-5 class machines and a message passing code for SP2 type machines are under development. Figure 9 shows results from the serial code run on a single RS/6000 machine for the supercritical evaporation of a submicron size argon droplet in equilibrium with its vapor. There are 996 atoms in the simulation. The goal is to simulate high numbers of supercritical hydrogen and oxygen molecules reacting in the gas phase; these efforts will require the computing power of SP2 class machines.

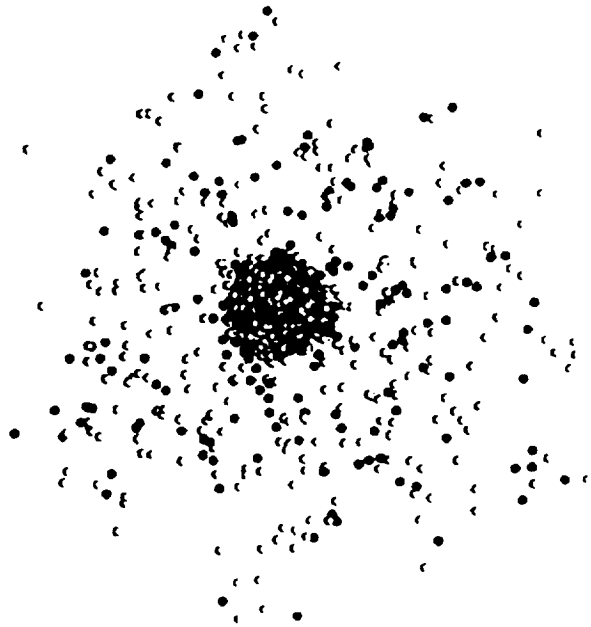


Figure 9. Subcritical liquid argon droplet in equilibrium with its vapor modeled using molecular dynamics. There are 996 atoms in the simulation.

The second major liquid propulsion research category - turbomachinery devices - features programs in bearings and seals and aero- and hydro-dynamics. Bearings and seals are critical elements in turbomachinery component designs. The Center program includes development of analytical methods to study the fluid-structure interaction between flexible foil bearings and lubricants, and evaluation of operating and lubrication conditions in rolling/sliding contacts with liquid oxygen. This work is funded by the Lewis and Marshall centers.

Detailed understanding of the complex fluid mechanics of flows through centrifugal pumps and turbines is necessary for improving the robustness and decreasing the cost of these critical liquid rocket engine components. The Center's research program in aero- and hydro-dynamics is focused on the development and improvement of CFD-based models for turbomachinery component design analysis. The emphasis here is on developing improved computational models, including improved turbulence models for pump and turbine geometries, advanced models for pump and inducer cavitation, and methods for enhancing the convergence rates of traditional algorithms for representative problems in turbomachinery.

In a Center project supported by Marshall Space Flight Center, a comparative study of by-pass transition and separation-induced transition to turbulence in turbines has been carried out using three different low-Reynolds-number k - ε models, using measurements made in transonic turbine cascades for comparison. It was found that the transition point can be predicted well with all three models in the presence of high free-stream turbulence provided that artificial dissipation is kept to a minimum. In both measurement and computation, the separation-induced transition results in a much sharper increase of local heat transfer rate than the nominal by-pass transition. The effects of Reynolds number, surface pressure gradient, freestream turbulence intensity, and freestream turbulence length scale on turbine blade transition have been studied in detail. A modification was introduced into the ε - equation to capture strong curvature effects. The ε - modification was found to capture the correct trend, but overpredict the results. Efforts are underway to modify the turbulence time scale of the production term in the ε - equation. Three-dimensional Navier-Stokes computations have been carried out for the Penn State turbine nozzle flow with good agreement obtained for mean-flow quantities, yaw angle, etc., and reasonable agreement for secondary vortex location and strength.

Advanced Propulsion Concepts

Our research in advanced propulsion concepts is oriented toward systems that offer significant performance benefits and mission enablement, but whose development timetable is at least one generation off in the future. Research is oriented toward building the technical foundation required for the practical use of these concepts. The specific systems under study range from hybrid motors for boost phase propulsion and rocket-based combined cycle systems for SSTO propulsion, to electro-thermal propulsion for space-based systems, to nuclear-thermal and fusion-based propulsion for interplanetary travel.

Rocket-based combined cycle (RBCC) systems are comprised of a rocket inside an airbreathing engine. Both engines are integrated to operate as a single unit to obtain advantages offered by each. A key feature of the RBCC is that it allows flight from take-off to orbit with a fixed geometry flow path. Center researchers are modeling the flowfield of these engines to search for ways to improve the efficiency of the flow processes that may lead to reduced engine size and weight and increased payloads. Present focus is on the combustor flowfield and the thermal choking process. The combustor is located downstream of the primary rocket. Since the engine flowpath has no converging sections, thermal choking is necessary to allow the flow to accelerate to supersonic velocities. Figure 10 shows contours of temperature and Mach number in a slightly divergent axisymmetric combustor flowfield. The flowfield is shown at a 5:1 geometric aspect ratio in the radial direction for clarity. Fuel is injected into the air stream at two radial locations. High temperature regions occur in the shear layers between the fuel and air. At the duct entrance, the flow is subsonic. Most of the heat addition occurs in the regions of subsonic flow. The sonic line is located near the point where duct wall divergence increases. At this point, the heat addition is slowed

significantly. The flow continues to accelerate to supersonic velocities downstream of this point. These results are part of a parametric study undertaken to determine the effect of combustor length on the flowfield.

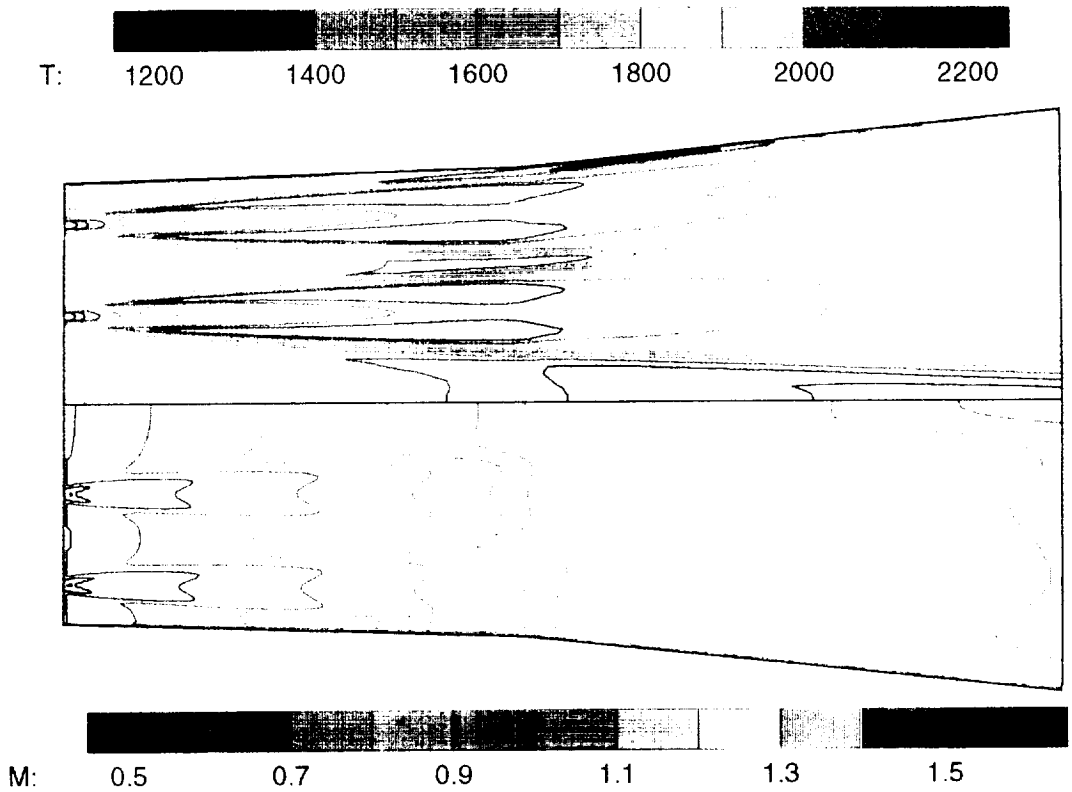


Figure 10. Predicted values of temperature and Mach number during thermal choking in a diverging axisymmetric combustor

Antimatter propulsion offers dramatic potential payoffs in terms of performance for future space missions. Inertial confinement fusion (ICF) can provide thrust for propulsion applications from plasma created by antiproton-induced ignition of fission reactions under conditions of high compression. A proof of principle experiment is underway at the SHIVA Star facility at the Phillips Laboratory to demonstrate subcritical neutron multiplication due to antiproton fission in targets compressed from 10 to 40 Mbar. Antiprotons are released from a Penning trap storage device, accelerated to 1.2 MeV by a radiofrequency quadropole, and focused onto the compressed deuterium target inside an imploding solid liner driven by the the SHIVA Star capacitor bank. Center researchers are studying ways to effectively transfer the momentum from the high energy propellant ions to thrust for propulsion. One facet of this work is the development of devices that can trap, store, and transport antiprotons that are generated in high-energy particle accelerators, such as those at CERN or Fermilab, to the site of the experiment. Figure 11 is a sketch of a trap proposed

by Center researchers. The trap is about 1 m tall and 0.5 m wide. To rid the trap of any residual air molecules that might interact with the antiprotons, the trap is first pumped to a high vacuum leaving just 100 molecules of air per cubic centimeter. The inner walls, maintained at a few degrees above absolute zero by liquid helium insulation, draw the remaining air particles toward them, and a combination of magnetic fields generated by permanent magnets and electric fields generated by a 10-volt battery keep the antiprotons in the center of the chamber.

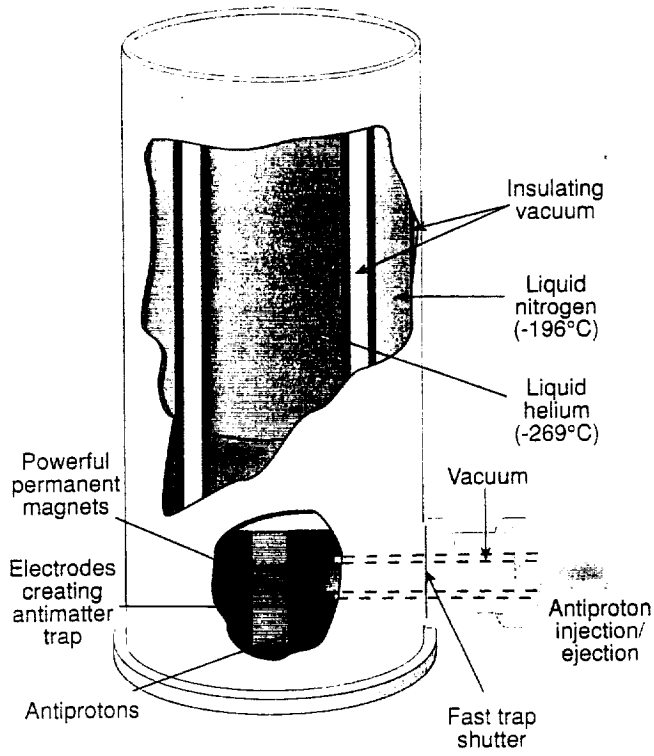


Figure 11. Penn State trap for storage and transport of antiprotons.

INTERACTIONS

The Center is an integral part of the space propulsion community in the U.S. From the outset, interactions with the propulsion community were strong, and as the Center matured, these interactions grew in a substantive way. Interactions occur in a variety of forms, including placement of Center graduates in government laboratories and in industry; Annual Symposia; participation on the Policy Advisory Board and in the NASA Seminar Series; externally-funded research grants and contracts; participation in graduate programs by full-time NASA employees; publications in technical journals and presentations at technical meetings; participation in numerous planning groups, advisory panels and workshops; and as editors of propulsion journals. Some of the highlights of these interactions are described below.

Our most important interaction with the propulsion community is one that will have a dominant long-term impact - the placement of our graduates in permanent employment positions in the industry. Since the Center's inception, 38 students with advanced degrees have commenced their professional careers in the U.S. propulsion community, either in industry or at government laboratories. NASA employees include three Center students at Lewis Research Center, three at Marshall Space Flight Center, one at Jet Propulsion Laboratory, one at Ames Research Center, and one at Langley Research Center. Students have also been placed with industrial propulsion employers, including Rocketdyne, Pratt and Whitney, UTRC, Martin Marietta, Fluent, CFD Research, Lockheed, Aerospace Corporation, General Electric, Allison, Garrett, and Westinghouse. Three Center students have participated in the Air Force Palace Knight program at Phillips Laboratory, where they will commence their professional careers after graduation. Table 4 lists graduates from the Center during the present reporting period, their degrees, and their current place of employment. Appendix A contains a summary of all students from the Propulsion Engineering Research Center who have gone on to careers in the U.S. propulsion community and elsewhere.

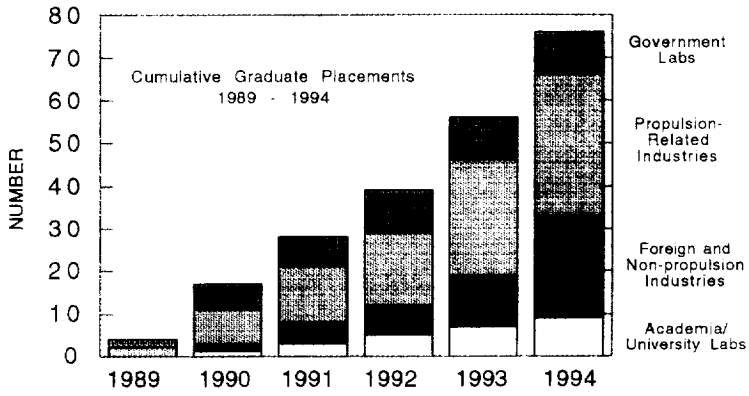


Figure 12. Graduate placement over the course of the Center.

As a complement to these students that have graduated and have been placed in the propulsion community, employees from NASA and the Air Force have taken advantage of the presence of the Center to return to school to obtain advanced degrees. Two employees from Marshall Space Flight Center, one each

from Lewis Research Center and Johnson Space Center, and three employees of the Air Force were enrolled in the graduate program during the present reporting period. Marshall Space Flight Center is also supporting five students through the Graduate Student Researcher Program.

Table 4. 1993 - 94 Graduates

Name	Degree	Current Employment
Michelle Beisler	MS	Schlumberger
Jeffrey Brown	MS	Patriot Consulting
Robert Burch	PhD	Propulsion Engineering Research Center
Yong-Seok Cho	PhD	Kumkin University, Korea
Kwang-Yoon Choi	PhD	Samsung Aerospace, Korea
Michael Evans	MS	Case Industries
James Frolich	MS	Ford Motor Company
Kumiko Higman	PhD	Georgia Tech
Tzung-Huei Huang	PhD	Taiwan University
Robert Kokal	MS	Owens - Corning Company
Jongguen Lee	PhD	Propulsion Engineering Research Center
Scott Lewis	PhD	Applied Research Laboratory, PSU
Simon Liou	PhD	Industrial Technology Research Institute
John Matulevich	MS	York International
John Merenich	MS	Applied Research Laboratory, PSU
Marty Milicic	MS	TRW
Randy Salizzoni	MS	General Dynamics, Electric Boat Division
Young-Hoon Song	PhD	Korea Institute of Machinery and Metals
Frank Tseng	PhD	CFSU, Taiwan
Corey Weaver	MS	Ford Motor Company
Myong Yoon	PhD	Yansei University, Korea

The Center's Annual Symposium is a formal avenue through which the Center disseminates its technical findings and interacts with the external propulsion community. The Annual Symposium is rotated between three locations: our own facilities at the Propulsion Engineering Research Center in University Park, the NASA Lewis Research Center in Cleveland, and the NASA Marshall Space Flight Center in Huntsville. This gives both our students and faculty and engineers and scientists at the two primary NASA propulsion centers opportunity to interact with each other on a regular basis, while minimizing travel constraints and meeting duplications. The Center's Symposia have developed into an important annual meeting, with its value enhanced by the three-way site rotation between Penn State and the Lewis and Marshall centers of excellence in propulsion.

The Sixth Annual Symposium was held at the NASA Lewis Research Center campus on September 9-10, 1994. A total of 47 papers were presented, representing contributions from academia; industry; and NASA and Air Force laboratories. Eighteen of these papers were given by students of the

Center. Table 5 gives the titles and authors of papers presented at the Symposium. The covered topics included:

- combustors and nozzles
- turbomachinery aero- and hydro-dynamics
- on-board propulsion systems
- advanced propulsion applications
- vaporization and combustion
- heat transfer and fluid mechanics
- atomization and sprays

The Seventh Annual Symposium is planned to take place at Marshall Space Flight Center in September, 1995.

Besides the Symposium, research results from the Center program are disseminated to the propulsion community by presentations at technical meetings, and through publications in appropriate journals. A cumulative list of publications, as well as special mentions, honors, panel participations, and presentations made by Center faculty and students in the present reporting period is provided in Appendix B.

Another distinct interaction between the Propulsion Center and NASA, the Air Force, and industry is through the Policy Advisory Board in which all these groups are represented. We have an outstanding group of individuals on our board (Table 1) who have been both active and effective. The Policy Advisory Board convened twice in the past year: a formal, structured visit coincident with the Annual Symposium; and a more informal visit in the Spring featuring detailed discussions with individual faculty and students.

Interactions between the Center and the propulsion community also take the form of financial support for research in specific areas. Externally-funded research projects in conjunction with Lewis Research Center, Marshall Space Flight Center, and the Jet Propulsion Laboratory; Air Force, Army, and Navy laboratories; and Pratt and Whitney, General Electric, Rocketdyne, and TRW were underway during the present reporting period. Center faculty and staff also perform service-oriented tasks for the propulsion community, such as editorial, peer review, and educational activities. Center faculty have been members of Technical Review groups for several NASA projects and have participated in numerous NASA and JANNAF panels, workshops, and consortia.

Table 5. Papers Presented at the Sixth Annual Symposium
NASA Lewis Research Center
Cleveland, OH

I. Combustors and Nozzles

Rapid Prototype Fabrication Processes for High Performance Thrust Cells - K. Hunt, T. Chwiedor, S. Diab, and R. Williams, Rocketdyne
Multi-Dimensional Combustor Flowfield Analyses in a Gas-Gas Rocket Engine - H.-H. Tsuei and C. Merkle, PSU
Thrust Augmentation of a Shrouded Nozzles - O. Patton, Cleveland State University, and L. Liou, Lewis Research Center
NASA Lewis Advanced Subsonic Combustor Program Overview - C.-M. Lee, Lewis Research Center
Characteristics of a Trapped Vortex (TV) Combustor - W.M. Roquemore, Wright Laboratory, and K.-Y. Shu, L. Goss, and D. Trump, Systems Research Laboratory
Density and Mixture Fraction Measurements in a GO_2/GH_2 Uni-element Rocket Chamber - M. Moser, S. Pal, and R. Santoro, PSU
CFD Assessment of the Carbon Monoxide and Nitric Oxide Formation from RD-170 Hot-Fire Testing at MSFC - T.-S. Wang and P. McConnaughey, Marshall Space Flight Center, S. Warsi, Sverdrup, and Y.-S. Chen, ESI, Inc.
The Effect of Incomplete Fuel-Air Mixing on the Lean Blowout Limit, Lean Stability Limit, and NO_x Emissions in Lean Premixed Gas Turbine Combustors - W.-P. Shih, J.G. Lee, and D. Santavicca, PSU
Performance of Ablative Chambers - H. Trinh, Marshall Space Flight Center

II. Turbomachinery Aero- and Hydro-Dynamics

Axial and Centrifugal Pump Meanline Performance Analysis - J. Veres, Lewis Research Center
SIMPLEX Turbopump Design - M. Marsh and P. Cowan, Marshall Space Flight Center
Computational Fluid Dynamics Analysis in Support of SIMPLEX Turbopump Design - R. Garcia, T. Benjamin, R. Williams, L. Griffin, J. Ruf, and J. Cornelison, Marshall Space Flight Center
Computation and Modeling of Aero-thermal Fields in Turbine Cascades and Strongly Curved Ducts - J. Luo and B. Lakshminarayana, PSU
CFD in the Design of a Water-Jet-Drive System - R. Garcia, Marshall Space Flight Center

III. On - Board Propulsion Systems

Performance Testing of a Fixed Configuration Microwave Arcjet Thruster - D. Sullivan and M. Micci, PSU
Orbital Maneuvering and Reaction Control Engines - E. Hurlbert, Johnson Space Center
Technology Advancements for On-Board Propulsion Systems - D. Byers, Lewis Research Center
Interface Issues for On-Board Propulsion Systems - F. Curran and S. Schneider, Lewis Research Center

IV. Advanced Propulsion Applications

Coupling Gravity, Electromagnetism, and Space-Time for Space Propulsion Breakthroughs - M. Millis, Lewis Research Center
Antiproton Catalyzed Microfission/fusion Propulsion - P.-R. Chiang, R. Lewis, G. Smith, R. Newton, J. Dailey, W. Werthman, and S. Chakrabarti, PSU
Advanced Propulsion at JPL - R. Frisbee, Jet Propulsion Laboratory
Magnetobraking: Use of Tether Electrodynamic Drag for Earth Return from Mars - G. Landis, NYMA
Low-Cost Booster and High-Performance Orbit Insertion Propulsion - R. Sackheim, TRW
Strutjet-Powered Reusable Launch Vehicles - A. Siebenhaar and M. Bulman, Aerojet, and S. Sasso and J. Schnackel, Martin Marietta
Technology Needs for Single Stage to Orbit Propulsion - S. Stoyanof and J. Monk, Marshall Space Flight Center

Table 5. Papers Presented at the Sixth Annual Symposium
NASA Lewis Research Center
Cleveland, OH
(Continued)

V. Vaporization and Combustion

LOX Droplet Vaporization in a Supercritical Forced Convective Environment - C.C. Hsiao and V. Yang, PSU
Shadowgraphy of Transcritical Cryogenic Fluids - R. Woodward and D. Talley, Phillips Laboratory, and T. Anderson and M. Winter, UTRC
High Energy Laser as a Combustion Stability Rating Device - K. Breisacher and L. Liou, Lewis Research Center
A Laser-Based Sizing/Velocimetry Technique to Investigate the Secondary Atomization of Aluminum Gel Propellants - D. Mueller and S. Turns, PSU
Metallized Gel Propellants: Oxygen/RP-1/Aluminum Combustion Experiments - B. Palaszewski, Lewis Research Center
Fundamental Phenomena on Fuel Decomposition and Boundary Layer Combustion Processes with Applications to Hybrid Rocket Motors - K. Kuo, Y.-C. Lu, M. Chiaverini, and G. Harting, PSU

VI. Heat Transfer and Fluid Mechanics

A Hydrogen-Oxygen Rocket Engine Coolant Passage Design Program (RECOP) for Fluid-Cooled Thrust Chambers and Nozzles - T. Tomsik, Lewis Research Center
The Least-Squares Finite Element Method for Low-Mach-Number Viscous Flows - S.-T. Yu, NYMA
Convergence Rate Enhancement of Navier-Stokes Codes on Clustered Grids - K.-Y. Choi and G. Dulikravich, PSU
The Effect of Thermodynamic Nonidealities and Transport Anomalies on Shear Layer Dynamics - J. Oefelein and V. Yang, PSU
Computational Fluid Dynamic Modeling of Rocket Based Combined Cycle Engine Flowfields - R. Daines and C. Merkle, PSU
Multidisciplinary Propulsion Simulation Using the Numerical Propulsion System Simulator (NPSS) - R. Claus, Lewis Research Center
Effects of Transverse Oscillatory Waves on Turbulent Boundary Layers - H.R. Jacobs, PSU
Validation of Two-Equation Turbulence Models for Propulsion Flowfields - M. Deshpande, S. Venkateswaran, and C. Merkle, PSU

VII. Atomization and Sprays

A Model to Predict the Conditions for Liquid Drop Breakup and the Resultant Mean Fragment Size - K. Wert and H.R. Jacobs, PSU
Analytical and Experimental Studies of Impinging Liquid Jets - H. Ryan, W. Anderson, S. Pal, and R. Santoro, PSU
Fluid Property and Operational Effects on Swirl Injector Droplet Sizes - G. Cox, Pratt & Whitney
The Effects of Turbulence on Droplet Drag and Secondary Droplet Breakup-Y.-H. Song, E. Coy, S. Greenfield, M. Ondas, T. Prevish, T. Spegar, and D. Santavicca, PSU
Shear Coaxial Injector Instability Mechanisms - T. Kaltz, M. Glogowski, and M. Micci, PSU
Acoustic Effects on Sprays - M. Pindera and A. Przekwas, CFD Research
Velocity-Modulation Atomization of Liquid Jets - J. Dressler, Fluid Jet Associates
Picosecond Imaging of Sprays - L. Wang, X. Liang, P. Galland,K. Breisacher, and L. Liou , Lewis Research Center, and P. Ho and R. Alfano, City College of New York/Institute for Ultrafast Spectroscopy and Lasers

SUMMARY

The Propulsion Engineering Research Center has been highly successful on all major fronts. We have had outstanding success in attracting quality graduate students, and have made substantial progress toward improving the diversity of the Center's student population. Our research program is relevant and productive. We have numerous meaningful interactions with the national propulsion community. The success of these endeavors is clearly attributable to the presence of the USERC Center.

The Center's presence has made it possible to attract some of the brightest young men and women in America to careers in propulsion, and the number of well-qualified U.S. students who chose to study at the Center has increased each year. Presently, 96 graduate students and 22 undergraduate students are participating in the research and educational activities of the Center. Thirty-eight students from the Center have graduated and are working in a propulsion area either in industry or at government labs. Seven of ten of our current graduate student population are U.S. citizens. We are also actively involved in encouraging the next generation of students to consider mathematics and science options through our participation in a number of K-12 outreach programs.

We established a successful minority program to enhance minority participation in the space program. Our first efforts were to provide minority undergraduate students in science and engineering with a research experience through the Summer Undergraduate Program. While the primary impact of that program was at the undergraduate level, it also had positive impacts on our graduate program. Our more recent minority initiative was designed to provide a more direct impact on our graduate program by establishing collaborative educational and research projects with minority academic institutions.

Our research program in space propulsion is deep and broad. Our area of emphasis is liquid propulsion, with focus areas in combustion devices and turbomachinery aero- and hydro-dynamics. The liquid propulsion research area is well established and is augmented by research on gas turbine and internal combustion engines. The breadth of the Center is enhanced by our efforts in solid propellant and advanced propulsion areas, which continues to be an effective means of exposing students to a broad propulsion perspective.

The Cryogenic Combustion Laboratory, which features capability for liquid and gaseous oxygen, hydrogen, and gaseous and liquid hydrocarbon propellants, is on line and in routine operation producing data for a number of research projects. Acquisition of experimental data at realistic operating conditions and geometries, and development and application of advanced non-intrusive diagnostic techniques for the severe rocket combustor environment are emphasized. This laboratory represents a unique research facility that enables us to make effective contributions both in terms of research and student education.

The Center has established strong ties with the space propulsion industry in many ways, including graduate placement, joint research projects, professional meetings, organized seminar series, and service on professional committees. We have particularly strong interaction with NASA's primary propulsion centers, LeRC and MSFC, the primary liquid propulsion contractors, and other propulsion-related government agencies.

These areas summarize the present state of the Propulsion Center. The quantity and quality of students attracted to space propulsion have been outstanding. The impact on minorities would have been impossible without the Center. Excellent experimental and computational facilities enhance the quality and relevance of our research results, with the Cryogenic Combustion Laboratory being of particular note. We have developed very strong interactions with the propulsion community through a variety of paths, and have attracted a substantial amount of external funds. We are providing a steady supply of students with advanced degrees who wish to start their professional careers in propulsion in the U.S. All of these areas of success are directly attributable to the presence of the Center established by the University Space Engineering Research Center program.

APPENDIX A.

CENTER PERSONNEL

APPENDIX A. CENTER PERSONNEL

A.1 PARTICIPATING FACULTY AND STAFF MEMBERS

Faculty

Marc Carpino	Associate Professor of Mechanical Engineering
Liming Chang	Assistant Professor of Mechanical Engineering
Fan-Bill Cheung	Professor of Mechanical Engineering
George S. Dulikravich	Associate Professor of Aerospace Engineering
Robert M. Edwards	Assistant Professor of Nuclear Engineering
Harold R. Jacobs	Professor and Head of Mechanical Engineering
Kenneth K. Kuo	Distinguished Professor of Mechanical Engineering
Budugur Lakshminarayana	Evan Pugh Professor of Aerospace Engineering
Thomas A. Litzinger	Associate Professor of Mechanical Engineering
Charles L. Merkle	Professor of Mechanical Engineering/ Director of Propulsion Engineering Research Center
Michael M. Micci	Associate Professor of Aerospace Engineering
Robert N. Pangborn	Professor of Engineering Science and Mechanics
Laura L. Pauley	Associate Professor of Mechanical Engineering
Richard A. Queeney	Professor of Engineering Science and Mechanics
Domenic A. Santavicca	Professor of Mechanical Engineering
Robert J. Santoro	Professor of Mechanical Engineering/Associate Director of Propulsion Engineering Research Center
Alok Sinha	Professor of Mechanical Engineering
Gerald A. Smith	Professor of Physics
Stephen R. Turns	Professor of Mechanical Engineering
Kon-Well Wang	Associate Professor of Mechanical Engineering
Vigor Yang	Professor of Mechanical Engineering

Staff

Cheryl Adams	Staff Assistant
William Anderson	Assistant Director
Penny Barr	Staff Assistant
Daniel Boone	Research Assistant
Robert Burch	Research Assistant
Yunho Choi	Visiting Research Associate
Jinzhang Feng	Research Associate
Jongguen Lee	Research Associate
Yu Cherng Lu	Research Associate
Marlow Moser	Research Assistant
Mary Newby	Staff Assistant
Tuqiang Ni	Research Associate
Sibtosh Pal	Research Associate
Connie Peters	Staff Assistant
John Raiser	Administrative Coordinator
Larry Schaaf	Research Assistant
Virginia Smith	Staff Assistant
Richard Steinberger	Research Associate
Sankaran Venkateswaran	Research Associate

A.2. TRAINEES

Name	Major	Degree Sought	Advisor	Expected Graduation Date
Philip Buelow	ME	PhD	Merkle	August '96
John Cramer	ME	PhD	Santoro	December '98
James Dailey	AERO	PhD	Smith	September '97
Michael Ondas	ME	PhD	Santavicca	December '95
Ken Philippart	AERO	MS	Santoro	May '95
Tom Prevish	ME	PhD	Santavicca	August '98
Douglas Schwer	ME	PhD	Merkle	December '96
Kevin Wert	ME	PhD	Jacobs	August '95
Lance Werthman	AERO	PhD	Smith	August '98
Joseph Wicker	AERO	PhD	Yang	May '96

A.3. RA'S SUPPORTED BY BASIC GRANT

Name	Major	Degree Sought	Advisor	Graduation Date
William Anderson	ME	PhD	Santoro	August '96
Michelle Beisler	ME	MS	Santoro	May '94
Bradley Bruno	ME	PhD	Santavicca	December '98
Christopher Chandler	ME	MS	Santoro	May '95
Martin Chiaverini	ME	PhD	Kuo	August '96
Wen-Wei Chu	ME	PhD	Yang	December '96
Kimberly Clemons	ME	MS	Santoro	August '98
Manish Deshpande	ME	PhD	Merkle	December '94
Todd Freyman	ME	PhD	Kuo	December '98
Andrea Frohman	ME	PhD	Merkle	December '98
Michael Glogowski	AERO	PhD	Micci	December '96
Jeffrey Grenda	ME	PhD	Merkle	December '94
Sreenath Gupta	ME	PhD	Santoro	December '95
Keith Hurley	ME	PhD	Carpino	December '97
Teresa Kaltz	AERO	PhD	Micci	December '97
Michael Korio	AERO	PhD	Lakshminarayana	December '97
Thomas Martin	AERO	PhD	Dulikravich	December '96
Marlow Moser	ME	PhD	Santoro	December '94
Harry Ryan	ME	PhD	Santoro	December '94
Randy Salizzoni	ME	MS	Kuo	June '94
Peter Strakey	ME	PhD	Santoro	December '94
Daniel Sullivan	AERO	PhD	Micci	May '95
Jennifer Sullivan	ME	PhD	Merkle	December '95

A.4. RA'S SUPPORTED BY EXTERNAL FUNDING OF CENTER PROJECTS

Name	Major	Degree Sought	Advisor	Graduation Date
Jeffrey Auston	AERO	PhD	Yang	May '96
Eric Boyer	ME	MS	Kuo/Brown/Lu	August '95
Jeffrey Brown	ME	MS	Kuo/Thynell	May '94
Robert Burch	ME	PhD	Cheung/Kuo	May '94
Suman Chakrabarti	ME	PhD	Smith	January '96
Yong-Seok Cho	ME	PhD	Santavicca	May '94
Kwang-Yoon Choi	AERO	PhD	Dulikravich	December '94
Daniel Cohen	ME	MS	Kuo	December '94
Edward Coy	ME	PhD	Santavicca	January '95
Russel Daines	ME	PhD	Merkle	May '95
Tom Demurray	ME	MS	Santavicca	May '95
Daric Escher	ME	PhD	Santoro	December '97
Michael Evans	ME	MS	Jacobs	December '94
Barry Fetherolf	ME	PhD	Kuo/Litzinger	December '93
Richard Field	ME	PhD	Kuo	December '93
Michael Foust	ME	PhD	Santoro	August '97
Jim Frolich	ME	MS	Santavicca	January '94
Stuart Greenfield	ME	PhD	Santavicca	January '95
George Harting	AERO	MS	Kuo	May '95
Roy Hilton	ME	MS	Merkle	May '94
George Hsiao	ME	MS	Yang	May '95
Joseph Hsieh	ME	PhD	Yang	August '95
Tzung-Huei Huang	FUEL SCI	PhD	Kuo/Thynell	August '94
Peter Huang	ME	PhD	Thynell/Kuo	December '93
Eric Hurlbert	ME	MS	Yang	May '95
John Hutt	ME	PhD	Yang	December '95
Aaron Johnson	ME	PhD	Merkle	August '99
Eun Sook Kim	ME	MS	Thynell	December '96
Robert Kokal	ME	MS	Kuo	December '93
Charles Kopicz	AERO	MS	Kuo	December '94
Seong-Young Lee	ME	PhD	Santoro	December '96
Jongguen Lee	ME	PhD	Santavicca	May '94
Simon Leonard	ME	MS	Santoro	January '94
Scott Lewis	ME	PhD	Sinha/Wang	May '94
Y.-C. Liau	ME	PhD	Yang	May '97
Simon Liou	ME	PhD	Santavicca	May '94
Jiang Luo	AERO	PhD	Lakshminarayana	December '95

A.4. RA'S SUPPORTED BY EXTERNAL FUNDING OF CENTER PROJECTS (continued)

Name	Major	Degree Sought	Advisor	Graduation Date
Carl Mallery	ME	PhD	Thynell	August '94
John Matulevich	ME	MS	Jacobs	August '94
Mark McMurray	ME	MS	Santavicca	June '94
John Merenich	ME	MS	Santoro	May '94
Anne-Geraldine Mouis	ME	PhD	Santoro	December '97
Donn Mueller	ME	PhD	Turns	January '95
David Nye	ME	PhD	Santavicca	January '94
Joseph Oefelein	ME	PhD	Yang	May '95
Jong Oh	ME	PhD	Yang	December '93
Chad Onlandt	ME	MS	Kuo	December '96
Brian Quay	ME	PhD	Santoro	December '96
Shamim Rahman	ME	PhD	Santoro	May '96
Stephen Ritchie	ME	PhD	Kuo/Thynell	December '94
Tae-Seong Roh	ME	PhD	Yang	August '95
Mark Schmidt	ME	PhD	Santoro	May '97
Wang-Ping Shih	ME	PhD	Santavicca	May '95
Young Hoon Song	ME	PhD	Santavicca	May '94
Timothy Spegar	ME	PhD	Santavicca	September '95
Hsin-Hua Tsuei	ME	PhD	Merkle	August '95
Abdullah Ulas	ME	MS	Kuo	December '96
Tienli Wang	AERO	PhD	Yang	August '96
Philip Walter	NUC ENG	PhD	Edwards	August '95
Todd Watson	ME	MS	Kuo	May '95
Sean Wilson	ME	MS	Brown/Kuo	December '94
Ta-Teh Wu	ME	PhD	Cheung/Hsieh	December '94
Chun-Liang Yeh	ME	PhD	Kuo	May '95

A.5. UNDERGRADUATES, 1993-1994

Name	Major	Advisor
Paul Alaksin	ME/PSU	Kuo
Jed Bailey	ME/Univ. of Wyoming	Santoro
Amy Cowan	AERO/PSU	Santoro
Brian Cwieroth	Physics/PSU	Smith
Carmen Falcone	ME/PSU	Micci
Janet Foster	AERO/Tuskegee	Lakshminarayana
Adam Gelwarg	IE/PSU	Santoro
Jonathan Halderman	E.SCI/PSU	Dulikravich
Gerardo Hernandez	ME/Univ. of Puerto Rico	Kuo
Michael Himes	ME/PSU	Santavicca
David Johnson	ME/PSU	Kuo
Bryan Koontz	ME/PSU	Santavicca
Katherine Kuznetsov	ME/Wisconsin	Merkle
Julian Laxton	ME/PSU	Kuo
Matt Mench	ME/PSU	Kuo
Mike Paulaskas	ME/PSU	Kuo
Frank Stone	ME/PSU	Santavicca
Julie Tolomeo	ME/PSU	Carpino
Yang-Sheng Tseng	ME/PSU	Kuo/Lu
Brian Watson	AERO/PSU	Smith
Eric Weaver	ME/PSU	Kuo
Karl Wilkerson	ME/PSU	Kuo

A.6. GRADUATE PLACEMENT

Name	Degree	Current Employment
Mahesh Athavale	PhD, 1989	CFD Research
Philip Balaam	PhD, 1991	Matra Espace
Michelle Beisler	MS, 1994	Schlumberger, Inc.
Jeffrey Brown	MS, 1994	Patriot Consulting
Robert Burch	PhD, 1994	Propulsion Engineering Research Center
Kristina Cairns	MS, 1990	Garrett
Gelsomina Cappuccio	MS, 1990	NASA Ames Research Center
J. L. Chen	PhD, 1991	Ford Motor Company
Yong-Seok Cho	PhD, 1994	Kukmin University
Kwang-Yoon Choi	PhD, 1994	Samsung Aerospace
Yun Ho Choi	PhD, 1989	The Ajou University
Anthony Colozza	MS, 1989	NASA Lewis Research Center
Samir Dagher	MS, 1991	Simulation Systems & Services
Laura DeSimone	MS, 1990	Naval Surface Warfare Center
Troy Dunn	MS, 1993	Martin Marietta
Michael Evans	MS, 1994	Case Industries
Barry Fetherolf	PhD, 1993	Martin Marietta
Mark Fisher	MS, 1990	NASA Marshall Space Flight Center
Jim Frolich	MS, 1994	Ford Motor Company
Y. T. Fung	PhD, 1991	General Physics
Kenneth Garner	MS, 1990	Westinghouse Electric
Christopher Gazze	MS, 1993	USAF
William Greene	MS, 1990	Martin-Marietta (NASA Marshall Space Flight Center)
Kumiko Higman	PhD, 1993	Georgia Institute of Technology
David Hoover		Boeing
Eric Hornchek	MS, 1993	XiLinx
Ashvin Hosangadi	PhD, 1990	SAIC
Tzung-Huei Huang	PhD, 1994	Associate Professor, Taiwan University
Taras Jarymowycz	PhD, 1991	Lockheed
Randall Kanzleiter	MS, 1991	Research Assistant, Renssalaer Polytechnic Institute
Michael Kline	MS, 1992	Orbital Sciences
Robert Kokal	MS, 1993	Owens-Corning Company
Jongguen Lee	PhD, 1994	Propulsion Engineering Research Center
Simon Leonard	MS, 1994	Rolls-Royce, Canada
Douglas Leone	MS, 1993	Southwest Research Institute
Scott Lewis	PhD, 1994	Applied Research Laboratory
Peter Liiva	MS, 1992	Texaco Fuels and Lubricants Laboratory
Norman Lin	PhD, 1993	Chung Shan Institute of Science & Technology
Simon Liou	PhD, 1994	Industrial Technology Research Institute, Taiwan
Yeu-Cherng Lu	PhD, 1992	Propulsion Engineering Research Center

A.6. GRADUATE PLACEMENT (Continued)

Name	Degree	Current Employment
John Matulevich	MS, 1994	York International
Kevin Mease	MS, 1991	General Electric
Lynn Medvetz	MS, 1992	SKF
John Merenich	MS, 1994	Applied Research Laboratory
Marty Milicic	MS, 1993	TRW
Jennifer Miller	PhD, 1993	Langley Research Center
Ellsworth Minor	PhD, 1989	Laboratory for Elementary Particle Science
Juergen Mueller	PhD, 1991	Jet Propulsion Laboratory
Gary North	PhD, 1992	NASA Lewis Research Center
David Nye	PhD, 1994	Allison Gas Turbines
Kirsten Pace	MS, 1991	Aerospace Corporation
Sibtosh Pal	PhD, 1990	Propulsion Engineering Research Center
Kwang-Seo Park	MS, 1990	Hyundai
Jih-Ping Peng	PhD, 1993	Seagate Technology
Rahul Puri	PhD, 1992	Allison Gas Turbine
Thomas Richardson	Phd, 1993	Allison Gas Turbine
Eric Roll	PhD, 1993	PSU Faculty, Behrend Campus
Randy Salizzoni	MS, 1991	General Dynamics, Electric Boat Division
Scott Sheffer	MS, 1993	Research Assistant, Princeton University
Charles Simchick	MS, 1990	Frick Company
Timothy Snyder	MS, 1990	UTRC
Young-Hoon Song	PhD, 1994	Korea Institute of Machinery & Metals
Robert Sonntag	MS, 1991	Pratt-Whitney
Michael Surrat	PhD, 1994	Air Force Phillips Laboratory
Frank Tseng	PhD, 1993	Director, Research Department, CFSU, Taiwan
I-Shih Tseng	PhD, 1992	Institute for Information Industry, Taiwan
Ronald Ungewitter	MS, 1989	Rocketdyne
Sankaran Venkateswaran	PhD, 1990	Propulsion Engineering Research Center
Brian Videto	PhD, 1992	Carrier Corporation
Corey Weaver	MS, 1993	Ford Motor Compnay
Jonathan Weiss	PhD, 1992	Fluènt
James Withington	PhD, 1992	Boeing
Roger Woodward	PhD, 1993	Air Force Phillips Laboratory
Seng-Rung Wu	PhD, 1992	Industrial Technical Research Institute
Andrew Yang	PhD, 1993	Earth Satellite Propulsion Division, Taiwan
Myong Yoon	PhD, 1993	Research Fellow, Yangsei University, Korea
David Yoset	MS, 1993	Stone & Webster Engineering
Donna Zelesnik	MS, 1992	Martin Marietta

APPENDIX B.

PUBLICATIONS, PRESENTATIONS, AND STUDENT AND FACULTY SPECIAL MENTIONS

B.1 JOURNAL AND OTHER REVIEWED PUBLICATIONS

B.2 CONFERENCE PROCEEDINGS AND PRESENTATIONS

B.3 AWARDS AND SPECIAL MENTIONS

APPENDIX B. PUBLICATIONS, PRESENTATIONS, AND STUDENT AND FACULTY SPECIAL MENTIONS

B.1 JOURNAL AND OTHER REVIEWED PUBLICATIONS

Alatas, B., J.A. Pinson, T.A. Litzinger, and D.A. Santavicca, "A Study of NO and Soot Evolution in a DI Diesel Engine via Planar Imaging," Paper No. 930973, SAE Transactions, 1993.

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Arold, M., C. Espey, T.A. Litzinger, D.A. Santavicca, and R.J. Santoro, "The Effect of Swirl on Spray and Combustion Processes in an Optically-Accessible, DI Diesel Engine," Soc. Automotive Engr. Transactions, SAE Paper No. 900396 (1990).

Arold, M., C. Espey, T.A. Litzinger, D.A. Santavicca, and R.J. Santoro, "A Study of Non-Swirling and Swirling Flow Fields and Their Effects on Spray and Combustion in an Optically-Accessible DI Diesel Engine," SAE Journal of Engines (1991).

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Carpino, Marc, and G.A. Domoto, "Investigation of a Flexible Disk Rotating Near a Rigid Surface," ASME Journal of Tribology, Vol. 110, No. 4, pp. 664-669 (1988).

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Chang, C.-L., and C.L. Merkle, "The Relation Between Flux Vector Splitting and Parabolized Schemes," Journal of Computational Physics, Vol. 80, No. 2, pp. 344-361 (1989).

Chang, C.-L., Y. Kronzon, and C.L. Merkle, "Time-Iterative Solutions of Viscous Supersonic Nozzle Flows," AIAA Journal, Vol. 26, No. 10, pp. 1208-1215 (1988).

Chen, B., et al., "Neutron Yields and Angular Distributions Produced in Antiproton Annihilation at Rest in Uranium," Phys. Rev. C, 45, 2332 (1992).

Chen, D.M., W.H. Hsieh, T.S. Snyder, V. Yang, T.A. Litzinger, and K.K. Kuo, "Combustion Behavior and Thermophysical Properties of Metal Based Solid Fuels," AIAA Journal of Propulsion and Power, Vol. 7, No. 2, pp. 250-257 (1991).

Chen, J.L., K.K. Kuo, and F.B. Cheung, "Theoretical Model of the Interior Ballistics Processes in an Electrothermal Gun," Journal of Propulsion and Power, Vol. 8, No. 3, pp. 655-666 (1992).

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Chen, S., and A. Sinha, "Probabilistic Method to Compute the Optimal Slip Load for a Mistuned Bladed Disk Assembly with Friction Dampers," ASME Journal of Vibration and Acoustics, Vol. 112, April, pp. 214-221 (1990).

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Chiang, P.-R., R.A. Lewis, G.A. Smith, J.M. Dailey, S. Chakrabarti, K.I. Higman, D. Bell, J.H. Degnan, T.W. Hussey, and B.W. Mullins, "Target Compression by Working Fluids Driven with Solid Liner Implosions," J. Appl. Phys. 76 (2): 637-647 (July 15, 1994).

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Choi, Y.-H. and C.L. Merkle, "The Application of Preconditioning in Viscous Flows," Journal of Computational Physics, Vol. 105, No. 2, April, 1993, pp. 207-223.

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Dulikravich, G.S. and K.-Y. Choi, "Sensitivity-Based Methods for Convergence Acceleration of Iterative Algorithms," Computer Methods in Applied Mechanics and Engineering (in press).

Dulikravich, G.S., "Aerodynamic Shape Design and Optimization: Status and Trends," AIAA Journal of Aircraft, Vol. 29, No. 5, Nov./Dec. 1992, pp. 1020-1026.

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B.2 CONFERENCE PROCEEDINGS AND PRESENTATIONS

Alatas, B., D.A. Santavicca, R.V. Bandaru, and S.R. Turns, "Semi-Quantatative One-Dimensional Measurements of Nitric Oxide Concentration in Turbulent Hydrocarbon-Air Diffusion Flames Using Laser-Induced Fluorescence," Fall Meeting of the Eastern States Section of The Combustion Institute, 1993.

Anderson, W.E., "Atomization of Impinging Liquid Jets," Wright-Patterson AFB, Dayton, OH, March 11, 1994.

Anderson, W.E., and R.J. Santoro, "Combustion Instability Phenomena of Importance to Liquid Rocket Engines," AFOSR Contractors Meeting in Propulsion, Crystal Bay, NV, June 5-10, 1994.

Bar-Gill, M., C. Puissant, M. Glogowski, and M.M. Micci, "Liquid Rocket Motor Combustion Stability Using Coaxial Injectors," AFOSR Contractors Meeting in Propulsion, Crystal Bay, NV, June 5-10, 1994.

Beisler, M.A., S. Pal, M.D. Moser, and R.J. Santoro, "Shear Coaxial Injector Atomization in a LOX/GH_2 Propellant Rocket," 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Indianapolis, IN, June 27-29, 1994.

Brankovic, A., K. Van Dyke, C.L. Merkle, M. Deshpande, and S. Venkateswaran, "Joint Validation of Turbulence Models for Rocket Engine Thrust Chamber Flows," 12th Workshop for Computational Fluid Dynamic Applications in Rocket Propulsion, Marshall Space Flight Center, Huntsville, AL, April 19-21, 1994.

Brown, J.J., S.T. Thynell, and K.K. Kuo, "Regression Behavior of Composite Layered Gun Propellants," accepted for presentation at the 30th JANNAF Combustion Subcommittee Meeting, Monterey, CA on November 15-19, 1993 (CPIA Publication 606, Vol. 1, pp. 375-386, March 1994).

Buelow, P.E.O., S. Venkateswaran, and C.L. Merkle, "High Aspect Ratio Convergence Acceleration in Multi-Dimensional Computations," 12th Workshop for Computational Fluid Dynamic Applications in Rocket Propulsion, Marshall Space Flight Center, Huntsville, AL, April 19-21, 1994.

Carpino, M. and J.-P. Peng, "Theoretical Performance of a Hydrostatic Foil Bearing," ASME Preprint No. 93-TRIB-37, presented at 1993 Joint ASME-STLE Tribology Conference, New Orleans, LA.

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Carpino, M., "Comparison of Experimental and Theoretical Performance of a Foil Bearing," presented at 1994 NASA Advance Earth to Orbit Propulsion Technology Conference.

Chiang, P.-R., R. Lewis, G. Smith, R. Newton, J. Dailey, W. Werthman, and S. Chakrabarti, "Antiproton Catalyzed Microfission/fusion Propulsion," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, September 13-14, 1994.

Chiang, P.-R., R.A. Lewis, G.A. Smith, C. Gazze, K. Higman, R. Newton, M. Chiaverini, J.M. Dailey, W.L. Werthman, S. Chakrabarti, and P. Cracraft, "An Antiproton Driver for ICF Propulsion," Paper No. AIAA-94-2926, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Indianapolis, IN, June 27-29, 1994.

Chiang, P.-R., R.A. Lewis, G.A. Smith, J.M. Dailey, W.L. Werthman, and S. Chakrabarti, "Challenges to Computing Fusion Plasma Thruster Dynamics," Paper No. AIAA-94-3268, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Indianapolis, IN, June 27-29, 1994.

Cho, Y.-S., and D.A. Santavicca, "The Effect of Incomplete Fuel-Air Mixing on Spark-Ignited Flame Kernel Growth," Fall Meeting of the Eastern States Section of The Combustion Institute, 1993.

Choi, K.-Y., and G. Dulikravich, "Convergence Rate Enhancement of Navier-Stokes Codes on Clustered Grids," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, September 13-14, 1994.

Daines, R.L., and C.L. Merkle, "Computational Fluid Dynamic Modeling of Rocket Based Combined Cycle Engine Flowfields," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, September 13-14, 1994.

Daines, R.L., and C.L. Merkle, "Computational Fluid Dynamic Modeling of the Rocket Based Combined Cycle Engine Flowfield," Paper No. AIAA-94-3327, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, June 27-29, 1994, Indianapolis, IN.

Deshpande, M., S. Venkateswaran, and C.L. Merkle, "Validation of Two-Equation Turbulence Models for Propulsion Flowfields," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, September 13-14, 1994.

Dulikravich, G.S. and T.J. Martin, "Inverse Problems and Design in Heat Conduction," 2nd IUTAM International Symposium on Inverse Problems in Engineering Mechanics, Ed. H. D. Bui and M. Tanaka, Paris, France, November 2-4, 1994.

Dulikravich, G.S. and K.-Y. Choi, "Convergence Rate Enhancement of Navier-Stokes Codes on Clustered Grids." 6th Annual Symposium of the Penn State - NASA Propulsion Eng. Research Center, NASA Lewis Research Center, Cleveland, OH, September 13-14, 1994.

Dulikravich, G.S., "Inverse Design and Optimization of Internally Cooled Configurations," 1994 Bucharest Heat Transfer and Thermodynamics Workshop, Bucharest, Romania, June 30-July 2, 1994.

Dulikravich, G.S. and K.-Y. Choi, "Global Sensitivity-Based Minimal Residual (SBMR) Method for Acceleration of Iterative Convergence Rates," 14th International Conference on Numerical Fluid Dynamics, Bangalore, India, July 11-15, 1994.

Dulikravich, G.S. and K.-Y. Choi, "Convergence Acceleration of Iterative Algorithms Using a Sensitivity-Based Minimal Residual (SBMR) Method," 12th Workshop for Computational Fluid Dynamic Applications in Rocket Propulsion, NASA Marshall Space Flight Center, Huntsville, AL, April 19-21, 1994.

Dulikravich, G.S. and T.J. Martin, "Inverse Determination of Temperatures and Heat Fluxes on Inaccessible Surfaces," 9th International Conference on Boundary Element Technology - BETECH 94, Ed: C. Brebbia and A. Kassab, Orlando, FL, March 16-18, 1994, pp. 69-76.

Dulikravich, G.S. and K.-Y. Choi, "Convergence Acceleration of Iterative Algorithms Using a Sensitivity-Based Minimal Residual (SBMR) Method," 12th Workshop for Computational Fluid Dynamic Applications in Rocket Propulsion, NASA Marshall Space Flight Center, Huntsville, AL, April 19-21, 1994.

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Dulikravich, G.S. and T.J. Martin, "Three-Dimensional Coolant Passage Design for Specified Temperatures and Heat Fluxes," AIAA paper 94-0348, AIAA Aerospace Sciences Meeting, Reno, NV, January 10-13, 1994.

Espey, C., J.E. Dec, T.A. Litzinger, and D.A. Santavicca, "Quantitative 2-D Fuel Vapor Concentration Imaging in a Firing D.I. Diesel Engine Using Planar Laser-Induced Rayleigh Scattering," SAE Paper No. 940682, SAE International Congress, 1994.

Fetherolf, B.L., Y.C. Lu, T.A. Litzinger, and K.K. Kuo, "A Comparison of the Physical and Chemical Processes Governing the CO_2 Laser-Induced Pyrolysis and Deflagration of M39 and M43," accepted for presentation at the 30th JANNAF Combustion Subcommittee Meeting, Monterey, CA on November 15-19, 1993 (CPIA Publication 606, Vol. 2, pp. 183-204, March 1994).

Glogowski, M., M. Bar-Gill, C. Puissant, T. Kaltz, M. Milicic, and M.M. Micci, "Shear Coaxial Injector Instability Mechanisms," Paper No. AIAA-94-2774, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Indianapolis, IN, June 27-29, 1994.

Hsiao, C.C., and V. Yang, "Liquid Oxygen (LOX) Droplet Gasification and Dynamics in a Supercritical Hydrogen Flow," AIAA Paper 94-2908, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Indianapolis, IN, June 27-29, 1994.

Hsiao, C.C., V. Yang, and J.S. Shuen, "Liquid Oxygen (LOX) Droplet Vaporization and Dynamics in Supercritical Forced Convective Environments," AIAA Paper 94-0682, AIAA 32nd Aerospace Sciences Meeting, Reno, NV, January 10-13, 1994.

Hsieh, S.-Y., and V. Yang, "A Unified Flow Analysis of Ramjet Propulsion Systems," AIAA Paper 94-3326, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Indianapolis, IN, June 27-29, 1994.

Huang, T.H., S.T. Thynell, and K.K. Kuo, "Partially Confined Hot Fragment Conductive Ignition: Part I-Modeling," accepted for presentation at the 30th JANNAF Combustion Subcommittee Meeting, Monterey, CA on November 15-19, 1993 (CPIA Publication 606, Vol. 1, pp. 387-400, March 1994).

Huang, T.H., S.T. Thynell, and K.K. Kuo, "Partially Confined Hot Fragment Conductive Ignition: Part II-Experiments," accepted for presentation at the 30th JANNAF Combustion Subcommittee Meeting, Monterey, CA on November 15-19, 1993 (CPIA Publication 606, Vol. 1, pp. 401-412, March 1994).

Jacobs, H.R., "Effects of Transverse Oscillatory Waves on Turbulent Boundary Layers," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, September 13-14, 1994.

Kaltz, T., M. Glogowski, and M. Micci, "Shear Coaxial Injector Instability Mechanisms," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, September 13-14, 1994.

Kaltz, T., J. Little, B. Wong, M. Micci, and L.N. Long, "Supercritical Droplet Evaporation Modelled Using Molecular Dynamics on Parallel Processors," Euromech Colloquium 324, The Combustion of Drops, Sprays, and Aerosols, Marseilles, France, July 25-27, 1994.

Kumar, B., S.T. Thynell, and K.K. Kuo, "Transient Combustion Behavior of a Thin Propellant Disc," accepted for presentation at the 30th JANNAF Combustion Subcommittee Meeting, Monterey, CA on November 15-19, 1993 (CPIA Publication 606, Vol. 1, pp. 271-282, March 1994).

Kuo, K.K., Y.-C. Lu, M. Chiaverini, and G. Harting, "Fundamental Phenomena on Fuel Decomposition and Boundary Layer Combustion Processes with Applications to Hybrid Rocket Motors," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, September 13-14, 1994.

Kuo, K.K., T.A. Litzinger, and W.-H. Hsieh, "Interrelationship Between Solid-Propellant Combustion and Material's Behavior," invited paper, presented and accepted for publication in Symposium Proceedings on Structure and Properties of Energetic Materials, Vol. 296, 1993, pp. 331-348.

Kuo, K.K., R.A. Kokal, P. Alaksin, M. Paulauskas, and L.S. Lee, "Flame-Spreading Phenomena in Fin-Slot Region of a Solid Rocket Motor," accepted for presentation at the 1993 JANNAF Combustion Subcommittee Meeting, Monterey, CA on November 15-19, 1993.

Kuo, K.K. and Y.C. Lu, "Modeling of Physicochemical Processes of Burning RDX Monopropellants," accepted for presentation at the 30th JANNAF Combustion Subcommittee Meeting, Monterey, CA on November 15-19, 1993 (CPIA Publication 606, Vol. 2, pp. 245-268, March 1994).

Lakshminarayana, B., "Three-Dimensional Flow Field in an Axial Flow Turbine, Including Rotor/Stator Interaction," NASA Lewis Research Center, December 2, 1993.

Lakshminarayana, B., "Experimental Investigation of Steady and Unsteady Flow Field Downstream of an Automotive Torque Converter Turbine and Stator," 5th International Symposium on transport Phenomena and Dynamics of Rotating Machines (ISROMAC-J), Maui, HI, May 8-11, 1994.

Lakshminarayana, B., "Turbulence Modeling and Computation of Turbine Aerodynamics and Heat Transfer," 12th CFD Workshop, NASA Marshall Space Flight Center, Huntsville, AL, April 1994.

Lakshminarayana, B., "Unsteady Flow Field in Axial Flow Turbines," Societe National D'Etude et de Construction de Moteurs D'Aviation, France, June 17, 1994.

Lakshminarayana, B., "The Unsteady Flow Field Investigation in Multistage Compressors and Turbines," Ecole Centrale de Lyon, France, June 21, 1994.

Lakshminarayana, B., "Recent Results on Multistage Compressor Flow Field," Allison Gas Turbine Co., General Motors Corporation, Indianapolis, IN, June 29, 1994.

Lee, J.G., T.-W. Lee, D.A. Nye, and D.A. Santavicca, "Lewis Number Effects on Premixed Flames Interacting with Turbulent Kármán Vortex Streets," accepted for presentation at the 25th Symposium (International) on Combustion and publication in the Symposium Proceedings, 1994.

Leone, D.M., and S.R. Turns, "Active Chlorine and Nitric Oxide Formation from Chemical Rocket Plume Afterburning," 32nd Aerospace Sciences Meeting, Reno, NV, January 10-13, 1994.

Liou, D., and D.A. Santavicca, "A Spark Ignition Model for Relight Problems in Aircraft Gas Turbine Engines," accepted for presentation at the 25th Symposium (International) on Combustion and publication in Combustion and Flame, 1994.

Long, L.N., M.M. Micci, and B.C. Wong, "Molecular Dynamics Simulations of Droplet Evaporation," Paper No. AIAA-94-2907, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Indianapolis, IN, June 27-29, 1994.

Luo, J., and B. Lakshminarayana, "Computation and Modeling of Aero-thermal Fields in Turbine Cascades and Strongly Curved Ducts," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, September 13-14, 1994.

Merkle, C.L., and J. Feng, "A Unified Time-Marching Procedure for Compressible and Incompressible Flows," (Invited Speaker), The International Conference on Hydrodynamics, Wuxi, China, October 30-November 3, 1994.

Merkle, C.L., J.M. Grenda, and S. Venkateswaran, "Numerical Simulation of High Frequency Combustion Instabilities in Liquid Rocket Engines," 25th International Symposium on Combustion, July 31-August 5, 1994, Irvine, CA.

Merkle, C.L., P.E.O. Buelow, and S. Venkateswaran, "Convergence Acceleration for Rocket Motor Combustion Calculations," 1994 Conference on Advanced Earth-to-Orbit Propulsion Technology, Marshall Space Flight Center, Huntsville, AL, May 17-19, 1994.

Merkle, C.L., D. Schwer, and H.-H. Tsuei, "Computational Analysis of Reacting Shear Layers in Rocket Engines," 12th Workshop for Computational Fluid Dynamic Applications in Rocket Propulsion, Marshall Space Flight Center, Huntsville, AL, April 19-21, 1994.

Merkle, C. L., "Application of Distributed Parallel Computers in Computational Fluid Dynamics," (Invited), OAI/OSC/NASA Symposium on Parallel and Distributed Computing," April 18, 1994, Columbus, OH.

Merkle, C. L., "Propulsion Research at Penn State," (Invited Talk), Tuskegee Institute, February 15, 1994, Tuskegee, AL.

Merkle, C. L., "The Role of Physics in Convergence of CFD Algorithms," (Invited Lecture), California Institute of Technology, November 16-17, 1993, Pasadena, CA.

Moser, M.D., S. Pal, and R.J. Santoro, "Density and Mixture Fraction Measurements in a GO_2/GH_2 Uni-element Rocket Chamber," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, September 13-14, 1994.

Moser, M.D., J.J. Merenich, S. Pal, and R.J. Santoro, "OH-Radical Imaging and Velocity Field Measurements in a Gaseous Hydrogen/Oxygen Rocket," AIAA Paper No. 93-2036, 29th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Monterey, CA, June 28-30, 1993.

Mueller, D., and S.R. Turns, "A Laser-Based Sizing/Velocimetry Technique to Investigate the Secondary Atomization of Aluminum Gel Propellants," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, September 13-14, 1994.

Mueller, D.C., and S.R. Turns, "A Theoretical Evaluation of Secondary Atomization Effects on Engine Performance for Aluminum Slurry Propellants," 32nd Aerospace Sciences Meeting, Reno, NV, January 10-13, 1994.

Ni, T., S.B. Gupta, and R.J. Santoro, "Suppression of Soot Formation in Ethene Laminar Diffusion Flames by Chemical Additives," 25th Symposium (International) on Combustion, University of California, Irvine, CA, August 1-5, 1994.

Oefelein, J., and V. Yang, "The Effect of Thermodynamic Nonidealities and Transport Anomalies on Shear Layer Dynamics," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, September 13-14, 1994.

Oefelein, J.C., and V. Yang, "Numerical Computation of Supercritical Combustion in Dilute Sprays," AIAA Paper 94-0683, AIAA 32nd Aerospace Sciences Meeting, Reno, NV, January 10-13, 1994.

Oh, J.Y., and V. Yang, "Interactions Between Shock and Acoustic Waves in a Supersonic Inlet Diffuser," AIAA Paper 94-2706, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Indianapolis, IN, June 27-29, 1994.

Pal, S., M.D. Moser, H.M. Ryan, M.J. Foust, and R.J. Santoro, "Flowfield Characteristics in a Liquid Propellant Rocket," AIAA Paper No. 93-1882, 29th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit, Monterey, CA, June 28-30, 1993.

Pinson, J.A., D.L. Mitchell, R.J. Santoro, and T.A. Litzinger, "Quantitative, Planar Soot Measurements in a D.I. Diesel Engine Using Laser-Induced Incandescence and Light Scattering," SAE Transactions, SAE932650, Society of Automotive Engineers, PA (1994).

Puissant, C., M.J. Glogowski, and M.M. Micci, "Experimental Characterization of Shear Coaxial Injectors Using Liquid/Gaseous Nitrogen," 6th International Conference on Liquid Atomization and Spray Systems, Rouen, France, July 18-22, 1994.

Ritchie, S.J., S.R. Wu, S.T. Thynell, and K.K. Kuo, "Shock-Induced, Hot Gas Conductive Ignition Characteristics of Solid Gun Propellants," accepted for presentation at the 30th JANNAF Combustion Subcommittee Meeting, Monterey, CA on November 15-19, 1993 (CPIA Publication 606, Vol. 1, pp. 283-294, March 1994).

Ryan, H.M., W.E. Anderson, S. Pal, and R.J. Santoro, "Analytical and Experimental Studies of Impinging Liquid Jets," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, September 13-14, 1994.

Santavicca, D.A., R.L. Steinberger, K.A. Gibbons, J.V. Citeno, and S. Mills, "The Effect of Incomplete Fuel-Air Mixing on the Lean Limit and Emissions Characteristics of a Lean Prevaporized Premixed (LPP) Combustor," AGARD 81st PEP Symposium, Rome, Italy, 1993.

Shih, W.-P., J.G. Lee, and D.A. Santavicca, "The Effect of Incomplete Fuel-Air Mixing on the Lean Blowout Limit, Lean Stability Limit, and NO_x Emissions in Lean Premixed Gas Turbine Combustors," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, September 13-14, 1994.

Song, Y.-H., E. Coy, S. Greenfield, M. Ondas, T. Prevish, T. Spegar, and D.A. Santavicca, "The Effects of Turbulence on Droplet Drag and Secondary Droplet Breakup," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, September 13-14, 1994.

Song, Y.-H., and D.A. Santavicca, "An Experimental Study of Droplet Motion in a Highly Turbulent Flow," Fall Meeting of the Eastern States Section of The Combustion Institute, 1993.

Song, Y.-H., and D.A. Santavicca, "An Experimental Study of Drag and Lift Forces Acting on an Evaporating Droplet Along a Curvilinear Trajectory," Fall Meeting of the Eastern States Section of The Combustion Institute, 1993.

Sullivan, D.J., and M.M. Micci, "Performance Testing of a Fixed Configuration Microwave Arcjet Thruster," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, Sept. 13-14, 1994.

Sullivan, D.J., and M.M. Micci, "Performance Testing and Exhaust Plume Characterization of the Microwave Arcjet Thruster," Paper No. AIAA-94-3127, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Indianapolis, IN, June 27-29, 1994.

Tseng, C.F., L.S. Tseng, W.W. Chu, and V. Yang, "Interactions Between Acoustic Waves and Premixed Flames in Porous Chambers," AIAA Paper 94-3328, 30th AIAA/ASME/SAE/ASEE Joint Propulsion Conference, Indianapolis, IN, June 27-29, 1994.

Tsuei, H.H., and C.L. Merkle, "Multi-Dimensional Combustor Flowfield Analyses in a Gas-Gas Rocket Engine," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, September 13-14, 1994.

Tsuei, H.-H., and C.L. Merkle, "The Dynamics of Reacting Shear Layers Adjacent to a Wall," 14th International Conference on Numerical Methods in Fluid Dynamics, July 11-15, 1994, Bangalore, India.

Walter, P.B. and R.M. Edwards, "Development of an Integrated Control and Health Monitoring Architecture for Nuclear Rockets," Proceedings of the 11th Symposium on Space Nuclear Power and Propulsion, Albuquerque, NM, Jan. 9-13, 1994.

Wert, K., and H.R. Jacobs," A Model to Predict the Conditions for Liquid Drop Breakup and the Resultant Mean Fragment Size," Propulsion Engineering Research Center Sixth Annual Symposium, NASA Lewis Research Center, Cleveland, Ohio, September 13-14, 1994.

Wilson, S.J., B.L. Fetherolf, P.W. Brown, and K.K. Kuo, "Surface Microstructure During Laser-Induced Pyrolysis and Combustion of RDX and XM39," accepted for presentation at the 30th JANNAF Combustion Subcommittee Meeting, Monterey, CA on November 15-19, 1993 (CPIA Publication 606, Vol. 2, pp. 167-182, March 1994).

B.3 SPECIAL MENTIONS AND COMMUNITY SERVICE

William E. Anderson:

Member, Technical Committee, Second International Symposium on Liquid Rocket Propulsion, Paris, France, June, 1995.
Session Chair, Propulsion Engineering Research Center Sixth Annual Symposium, Cleveland, Ohio, September 13-14, 1994.

George S. Dulikravich:

Member, AIAA Technical Committee on Space Processing, May 1993-present.
Member, ASME International Technical Committee on Turbomachinery, Gas Turbine Division, October 1984-present.

Michael Foust:

AIAA Liquid Propulsion Technical Committee Graduate Scholarship Award.

Kenneth K. Kuo:

Editor, Non-Intrusive Combustion Diagnostics to be published November 1994.
Volume Editor, AIAA Progress Volume entitled Recent Advances in Spray Combustion, to be published in two volumes: Volume I to be published August 1995 and Volume II to be published December 1995.

Budugur Lakshminarayana:

Member, NASA Marshall Space Flight Center Turbine Technology Team.
Member, NASA Marshall Space Flight Center Pump Technology Team.
Member, AFOSR Military Aircraft Engine Advisory Group.
1994 Air Breathing Propulsion Award, June 1994.

Charles L. Merkle:

Associate Editor, Journal of Propulsion and Power, 1991-1994.
Organizing Committee, Second International Symposium on Liquid Rocket Propulsion: Combustion Devices, Paris, France, June, 1995.
Session Chair, The International Conference on Hydrodynamics, Wuxi, China, October 30-November 3, 1994.
Session Chair, Propulsion Engineering Research Center Sixth Annual Symposium, Cleveland, Ohio, September 13-14, 1994.
Session Chair, 14th International Conference on Numerical Methods in Fluid Dynamics, Bangalore, India, July 11-15, 1994.
Session Chair, 30th Joint Propulsion Conference, Indianapolis, IN, June 27-29, 1994.
Member, Peer Review Panel on Numerical/Analytical/Experimental Study of Fluid Dynamic Forces in Seals, NASA Lewis Research Center, 1991-1996.
Member, NASA Propulsion Synergy Group, Executive Committee, 1991-Present.

Michael M. Micci:

Member, AIAA Liquid Propulsion Technical Committee.

Joseph Oefelein:

AIAA Liquid Propulsion Technical Committee Graduate Scholarship Award.

Harry M. Ryan:

Graduate student mentor for Space Grant high school students.

Domenic A. Santavicca:

Editorial Advisory Board Member, Combustion Science and Technology, 1992-1996.
Executive Board Member, Society of Automotive Engineers, Fuels and Lubricants Activity.
Consultant to Westinghouse Electric Company, General Electric Power Generation, and Lubrizol on laser diagnostics for combustion research.

B.3 SPECIAL MENTIONS AND COMMUNITY SERVICE (Continued)

Robert J. Santoro:

Member, NASA Microgravity Combustion Discipline Working Group, 1991-1994.
Member, Science Panel for Advanced Combustion Modules Conceptual Design Review, NASA Lewis Research Center, October 13-14, 1993.
Chairman, Eastern Section of the Combustion Institute, 1993-1995.
Mechanical Engineering Department Head's Outstanding Faculty Member, 1992-93.
Editorial Board, Combustion and Flame, 1994-2000.

Stephen R. Turns:

Member, The Combustion Institute Program Committee, 25th Int'l Symposium on Combustion.
Co-Organizer, Combustion and Flow Diagnostics Session, SAE Int'l Congress and Exposition.
Proposal Review Panel, National Aeronautics and Space Administration, 1993.

Vigor Yang:

Associate Editor, Journal of Propulsion and Power, 1991-1997.
Co-Chairman, Technical Committee, Second International Symposium in Liquid Rocket Propulsion, Paris, France, June, 1995.
Member and Chair of Technical Program Subcommittee, AIAA Propellants and Combustion Technical Committee, 1992-present.
Editor, Special Issue of Journal of Propulsion and Power on Solid-Propellant Rocket Motor Interior Ballistics and Combustion of Energetic Materials, 1994-1995.
Mechanical Engineering Department Head's Outstanding Faculty Award, 1993-1994.
NATO/AGARD Consultant to ONERA (France), March, 1994.
Member of Editorial Advisory Board, Journal of Combustion, Explosion, and Shock Waves, 1994-present.

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